MODELLING GROWTH OF A TROPICAL RAIN FOREST IN EAST KALIMANTAN, INDONESIA

A Thesis
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of
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by
Nur Masripatin

University of Canterbury
Christchurch, New Zealand
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CONTENTS

ABSTRACT

A study on modelling growth of individual trees in a tropical rain forest in East Kalimantan of Indonesia using PT. ITCI and PT. INHUTANI I data was conducted with the main aims being to provide a tool for predicting growth and yield, and to offer recommendations to improve the planning of timber harvests and management of the forests.

Individual tree-based distance-independent modelling was the approach used to predict diameter growth of trees in the above forests. This approach was considered to be more applicable to selection cutting and planting system called TPTI (Tebang Pilih Tanam Indonesia), the silvicultural system applied for achieving management goals at harvest in tropical rain forests in Indonesia.

Various ways for grouping species (using maximum attainable size and growth characteristics) were examined and different functional forms (linear models, probabilistic and modified beta functions, asymptotic nonlinear equations) were tested through several steps using PT. ITCI data. An empirical approach using the above characteristics was found to offer a useful way to aggregate species for PT. ITCI data. A modified form of the Gompertz projection equation which incorporated stand attributes and locality factors proved to be the best model among functional forms tested in this study. The modified Gompertz projection form was then used to model PT. INHUTANI I and the combined PT. ITCI/ PT. INHUTANI I data, using the same criteria for species aggregation as for the PT. ITCI data (maximum attainable size and growth characteristics).

The overall best performance shown by the Gompertz projection equation (an asymptotic nonlinear equation) among the functional forms tested for PT. ITCI data, was the major contribution from this study to individual tree-based growth modelling research in tropical rain forests. Individual tree-based modelling in this type of forest, for reasons unknown has traditionally relied heavily on the use of linear models. Outcomes from modelling PT. ITCI, PT. INHUTANI I, and the combined PT. ITCI/PT. INHUTANI I data, provide useful insights into what further research is needed in modelling tropical rain forests in these two localities. Although the growth models developed in this study still require further improvements, these models offer a useful guide for improving silvicultural prescriptions which are currently based on an assumed tree diameter growth rate of 1 cm/year for commercial trees.

Abbreviations, acronyms, symbol, and terminology

Species groups :

LF : Large faster growing species
LS : Large slower growing species
MF : Medium faster growing species
MS : Medium slower growing species
SF : Small faster growing species
SS : Small slower growing species
UF : Other faster growing species
US : Other slower growing species

Note :
UF & US refer to species, information about the maximum attainable size of which was not available.

Selected species groups for PT. ITCI data :

LUF : Large and other faster growing species
LMUS : Large, medium, and other slower growing species
MeSF : Medium and small faster growing species
SmaS : Small slower growing species

Selected species groups for PT. INHUTANI data :

LF, LS, MeSF, UF ; same as above
MSUS : Medium, small, and other slower growing species.

Species groups for the combined PT. ITCI/PT. INHUTANI I data :

- 4 species groups of DF, DS, NF, NS
- 8 species groups of LF, LS, MF, MS, SF, SS, UF, US
- 10 species groups of LF, LS, MF, MS, SF, SS, UF, US, DF, DS, NF, NS

LF, LS, MF, MS, SF, SS, UF, US: same as above
DF : faster growing dipterocarp species
DS : slower growing dipterocarp species
NF : faster growing non-dipterocarp species
NS : slower growing non-dipterocarp species

Note :
For 10 species groups, DF, DS, NF, and NS refer to species existing only in either PT. ITCI or PT. INHUTANI I data

Variables in the equations :

alt : altitude above see level in m

ci : competition index (accumulated basal area of trees in a sub-plot, excluding the subject tree=G_{sp}-g in m^2/0.01 ha)

d : initial tree diameter in cm

d_i : diameter increment in cm/year

d_1 : diameter at time 1 in cm

d_2 : diameter at time 2 in cm

G : plot basal area in m^2/ha

$G_{>d}$: overtopping basal area (accumulated basal area of trees with diameter > 30 c) in a plot level in m^2/ha

geom : geomorphology (takes up the value 1 for a plot located in an asymmetric non-oriented hill with steep slope; 2 for a plot located in a linear ridge system with steep to very steep dipslope; 3 for a plot located in a mountaneous area with steep dissected dipslope)

G_{sp} : sub-plot basal area in m^2/0.01 ha

$G_{sp>d}$: accumulated basal area of trees with diameter greater than the subject tree in a sub-plot in m^2/0.01 ha

loc : localities, a variable added to combined data (1 for PT. ITCI data and 0 for PT. INHUTANI I data)

lov : logged or virgin/unlogged (takes up the value 1 for a logged plot and 0 for an unlogged plot)

SQ : dummy variable for soil characteristics (1 for better soil and 0 for poor soil) (for PT. ITCI data)

SC : soil category, takes up the value 1 for UC3 (udults soil groups, cleistone soil parent material, with well drained condition) and 0 for other soil categories (for PT. INHUTANI I data)

tci : a measure of tree dominance ($1-(G_{sp>d}/G_{sp})$)

t_2-t_1 : years between consecutive measurements

Note:

d refers to diameter at breast height or above buttresses/irregularities.

Others :

α, β, γ : parameter to be estimated

act : actual values

pred : predicted values

resid : residuals

Int.	: Intercept
RMS	: Residual Mean Squares
CFI	: Continuous Forest Inventory
PSP_s	: Permanent Sample Plots
TSP_s	: Temporary Sample Plots
BPK	: Balai Penelitian Kehutanan (Forest Research Institute)
ODA	: Overseas Development Assistnace
PT. ITCI	: International Timber Corporation Indonesia (Forestry private owned enterprise)
PT. INHUTANI I	: Industri Hutan Indonesia (Forestry state owned enterprise)
Dipterocarps	: refer to species of *Dipterocarpaceae* (including *Cotylelobium, Dipterocarpus, Dryobalanops, Hopea, Shorea, Upuna, and Vatica*)
Dipterocarp forests	: refer to forests with predominant species belonging to *Dipterocarpaceae* (mostly in South-east Asia's tropical rain forests)
Locality factors	: refer to plot conditions (logged or unlogged, altitude, site quality characteristics , geomorpholgy) and source of data (PT. ITCI or PT. INHUTANI I)
Number of observations	: refer to number of measurements taken on a tree/species/species group

[i] readers could use the loose copy of "Abbreviations, acronyms, symbol, and terminology" in the attached envelope for ready reference.

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(note : HC=hard copy; DF=diskette form)

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CHAPTER 1
INTRODUCTION

Indonesia is an archipelagic country which covers about 193 million ha of land area. More than seventy percent (140.5 million ha) of the area is classed as forest which is divided into protection forest (33.8 million ha), nature reserve (18.8 million ha), convertible forest for other purposes (26.6 million ha), and production forest (64.3 million ha) (MOF 1994). Natural tropical rain forests occupies more than 90 % of the total production forest area. This study of tree growth relates to a selected production forest which form a small part of this tropical rain forest.

1.1. BACKGROUND OF STUDY

Logging of natural tropical forests in Indonesia started intensively in the 1960s when the HPH (concession holding) system was introduced (MOF and FAO 1990). Since then, timber products have become the second largest export of Indonesia after petroleum (MOF, 1994).

Natural rain forest (production forest) in Indonesia is managed under a selection cutting and planting system (TPI), with cutting cycles of around 35 years. Guidelines from the Ministry of Forestry allowed only trees with minimum diameter (dbhob) of 50 cm to be cut, except for *Gonystilus bancanus* and *Diospyros ebenum* which are allowed to be cut in lower diameter limit. Following logging, at least 25 trees per ha of commercial species with diameter between 20 – 49 cm must be retained in logged-over forests for possible harvest at time of the next cutting cycle. In this silvicultural system, it is assumed that if average tree diameter increment is 1 cm per year, those 25 or more trees are expected to reach the minimum allowable tree diameter of 50 cm or more to be available to be cut in the next cutting cycle. While it simplifies the procedure for estimating future forest status in the absence of reliable information regarding tree growth in this type of forests, this assumption is not sufficiently robust to satisfy the concept of growth dynamics for this forest system.

Tropical rain forest is a complex system, and the growth dynamics of a large number of tree species are still poorly understood. This forest resource is important for the Indonesian

economy, and at the same time also serves as a regulator of regional and global climate through evapotranspiration and carbon sequestration (see Panayotou and Ashton, 1992). Indonesian commitment to Agenda 21 of the Rio Declaration and ITTO guidelines for natural forest management, means admitting the urgent need for: 1) high quality of planning and execution of forest management, and 2) effective and up-to-date monitoring to control annual cut levels and to protect habitat and environment, supported adequately by scientific and application oriented research (Bruenig, 1993). All of those imply the importance of growth and yield studies for tropical rain forests.

1.2. PROBLEM STATEMENT

The commercial purpose of forest management on the one hand and the concept and demands of sustainability on the other, should convince policy makers and planners of the need to know the status of forest resources in the future. Growth models have been demonstrated to offer reliable means for forecasting stand dynamics for management purposes, for example: examine harvesting options, determine sustainable yield capability, and also permit prediction of future stand structure.

Studies of growth and yield in mixed-species forests have been done mostly in temperate forests using methodology that is not readily adaptable to tropical conditions and the emphasis in which is not always directly useful for the purpose of harvest and forest management planning of the tropical rain forests. Despite the problems encountered in modelling complex tropical rain forests, developing an appropriate methodology for predicting future forest stands using whatever information is readily to hand, is crucial to their sound management.

For the selection cutting system where guidelines from the Ministry of Forestry determine the minimum diameter of trees of various species that are allowed to be cut, individual tree-based models, which maintain species identity and which utilize diameter growth as the response variable, have practical advantages. Most individual tree-based models have been developed using linear (empirical) equations, although possible pitfalls of this type of models are well recognized. Asymptotic non-linear equations are known to have more biological basis than linear models, but the fact that age is an important driving variable has limited the use of these equations for species of indeterminate age. Attempts to use

asymptotic non-linear equations without involving age variables have been conducted by some researchers in temperate regions, with limited data and simple stand structures. Reports of its application in a complex forest system such as tropical rain forests have not been found.

1.3. SCOPE OF THE STUDY

This study dealt with a selected tropical rain forest of PT. ITCI and PT. INHUTANI I in East Kalimantan, Indonesia: it focused on developing growth modelling methodology in order to improve timber harvest and forest management planning, using resources currently available. The methodology developed in this study contributes particularly to further research, while at the same time it can provide useful information for forest management.

Individual tree-based distance-independent modelling was used to predict diameter growth of the forest in the two localities. Modelling in this study dealt with a large number of species, and so species grouping was a critical part of the research. Various ways of grouping species were explored, and different functional forms were identified and evaluated in order to obtain tree diameter growth models which best, among those tested, characterize growth of the forest under study.

Modelling efforts involved analyzing the potential of asymptotic non-linear equations for individual tree-based modelling of the forests under study, and other functional forms which have been commonly used for modelling tropical rain forests. Problems in fitting non-linear models to growth data from tropical rain forests (ageless stands) have been addressed in several previous research publications, but detailed discussions in comparing linear and non-linear models was not found. There has also been extensive use of linear equations for individual tree based modelling in mixed-species in temperate as well as in tropical forests. It was part of this study to compare the potential of both types of equation (non-linear and linear forms) for modelling tropical rain forests.

1.4. RESEARCH OBJECTIVES

The overall aim of this study was to develop growth modelling methodology to improve planning of timber harvests in the short and medium term together with forest

management generally, in order to assist in managing a selected area of Indonesian rain forest sustainably.

This overall aim was further broken down as follows :

1. to analyze and identify appropriate techniques for modelling growth of the selected tropical rain forest in Indonesia, given the re-measured growth plot and general inventory data bases, in the light of perceived planning needs;

2. to make a recommendation, based on this analysis, of the yield forecasting methodology most suitable for forest management and timber harvest planning in the selected situation;

3. to gain insight into what updating of growth plot data over time is necessary for enhancing growth modelling options in future research studies;

4. to acquire a better understanding of the forest dynamics in the chosen area in order to help manage the forest resource in a sound and sustainable manner.

As a prelude to the modelling analysis carried out in this study, pertinent literature is reviewed in the next chapter.

CHAPTER 2
LITERATURE REVIEW

Three main subjects, (1) growth modelling in general, (2) tropical rain forest systems, and (3) some aspects of modelling a tropical rain forest system, are reviewed in this chapter. The first outlines the nature of existing forest growth models in general and provides an overview of the development of both single species (even-aged) and mixed-species (uneven-aged) growth modelling. The second presents a brief exposition of tropical rain forest systems generally, and Indonesia's tropical forest particularly. The last part of the chapter emphasizes modelling options suitable for tropical rain forests; the need for grouping species, individual tree-based distance-independent growth modelling together with a rationale of the approach used in this study, variables included in the model, measures of competitions and site qualities, and implications for the research carried out here.

2.1. GROWTH MODELLING

A model can be defined as a simplification of a complex reality. A model is also abstract, and so a model is an abstraction or simplification of a system (Hall and Day, 1977; Botkin, 1993). Goodman (1975) according to Hall and Day (1977), viewed a model as a device for predicting behavior of a complicated, poorly understood entity from the behaviour of components that are well understood.

Hall and Day (1977) stated that one of the most important uses of models is in assisting a scientist with conceptualizing, organizing, and communicating complicated phenomena in order to help in understanding and assessing these phenomena. Another prime use of models, according to the above authors, is to test the validity of field measurements and the assumptions derived from them. They argued that '*if the model and the real world disagree, then one or the other, or both, are imperfectly known, and tracing the error will almost certainly increase our understanding of the real or the model system*'.

Growth models and modelling in this study reflect the definitions of growth proposed by Vanclay (1994b). '*Growth refers to the increase in dimensions of one or more individuals in a forest stand over a given period of time*' and '*a stand growth model is an abstraction of*

the natural dynamics of a forest stand, and may encompass growth, mortality and other changes in stand composition and structure'. Growth models nowadays normally refer to mathematical equations or systems of equations, used to relate actual growth rates to measured trees, stands, and site factors (Bruce and Wensel, 1988).

2.1.1. Types of model

Two categories of model can be distinguished in terms of those for understanding and others for prediction (Bunnel, 1989). Gap models and process models can be categorized as models for understanding because these models capture the essential dynamics of the system and aim to explain the behaviour of systems (e.g. Landsberg, 1981; Botkin, 1993; Bossel, 1991; Bossel and Krieger, 1994). The dynamics of gap models are determined by inter-species competition processes for light at forest gap level, while the ones of process models are determined by physiological processes at tree level (Bossel, 1991). These models are mechanistic because they involve attempts to describe the responses of the system to changing conditions on the mechanisms which determine the behaviour of the system (Landsberg, 1981). Models used for forest management are included in models for prediction, and considered to be management-oriented growth models. These models are aimed at providing information on behaviour of the system without representing the underlying mechanisms affecting the responses. Moreover, because they are built for management purposes, these models mostly use predictor variables which can be accurately and readily determined from field records, their main aim is the applicability for routine management.

The importance of process-based and management oriented models for sustainable management of a complex system such as tropical rain forests is well recognized. The driving variables for these two types of model, however, are quite different (Bruce and Wensel, 1988). The process-based models '*tend to require large amounts of very specific parameter values that are available only for special cases, and the models cannot be tested in a rigorous, statistically sound sense*' (Mohren and Burkhart, 1994). Management-oriented growth models, on the other hand, depending on the complexity of the models, use tree or stand variables, measures of site qualities and competition without reference to the growth processes *per se*. They are based mainly on data obtained from field measurements on successive occasions.

The main aim of process-based models is understanding and explaining the behaviour of particular ecosystems, with less emphasis on predicting with a certain degree of accuracy

acceptable for forest management decisions (Mohren and Burkhart, 1994). Management-oriented growth and yield models may sacrifice specific details of growth processes in order to achieve greater efficiency and accuracy in providing information for forest management (Vanclay, 1994b). The different emphases contained in each of these two kinds of model, and the fact that each of them is useful for its own purpose, make it seem unlikely that these two models will replace one another. Moreover, based on the development of these two models to date, it is also unlikely that growth and yield models will be replaced by detailed process-based models in making practical forest management decisions (Bruce and Wensel, 1988; Goulding, 1994; Mohren and Burkhart, 1994; Adlard, 1995).

Reviewing in detail the differences between process-based and management oriented growth and yield models is not attempted here. Rather, they have been outlined briefly to indicate the focus of this study, to underline the relative importance of these two types of model in order to manage tropical rain forests sustainably, and to help in analysing and evaluating the outcomes of this study.

The scope of this study falls into *management oriented growth and yield models* based on the category of models stated earlier, and so, further review will focus on this type of model only. Growth and yield models have been demonstrated to be reliable tools for prediction of future yield, which is central for sound forest management. Modelling growth and yield should be able to provide a means for prediction of stand structure at some future date, and information on stand productivity for different site conditions and circumstances offering silvicultural alternatives.

Daniels and Burkhart (1988) divided management-oriented forest growth and yield modelling approaches into three broad categories : whole stand models, size class models, and individual tree models. A similar categorisation was proposed by Vanclay (1994b): whole stand models, size class models, and single tree and tree list models. A short review of the above three categories is given below:

Whole stand models. Growth and yield are predicted using crop population statistics such as stocking/ha, basal area/ha, stand height, without determining details of the individual trees in the stand. Whole stand models have already shown great potential as a simple technique to predict plantation yield, but are not flexible enough to provide useful estimates of growth and yield in tropical rain forests where there are many species and a wide range of stem size and tree age.

Size class models. Classes of trees within stands are identified and characterised as the basic unit of modelling. This approach is a compromise between whole stand and single tree or tree list models. It provides sufficient information for many forest management applications and has been widely used to model the growth of natural forests (eg. Buongiorno and Michie, 1980; Mendoza and Setyarso, 1986; Chai and Sia, 1989). Some major limitations may arise in using this approach to model tropical rain forest systems with many species and a wide range of stem classes.

Individual tree or single tree and tree list models. Individual trees are identified and individual tree characteristics are used as the basis for modelling. A list of attributes (e.g. species, dbh, stem defects) is recorded for each individual tree. Tree list models simulate the number of trees per ha in aggregate from individual tree records, and they have been widely used for uneven-aged mixed forests growing in both temperate and tropical climates (eg. Wykoff *et al.,* 1982; Wykoff, 1986; Stage and Wykoff, 1993; Vanclay, 1994b). They are likely to form the basis of many mixed-forest growth models in the future.

The choice between the three types of models of course depends on the population being modelled, the degree of precision required, and resources available to build the models. An attempt to compare these three types of model was conducted by Daniels and Burkhart (1988). They compared pdf-based diameter distribution models, whole stand models, and individual tree distance-dependent models; and found that all performed similarly for simple yield estimates. They also noted that individual-tree models, while providing greater detail in flexibility in simulating management alternatives, took much longer to execute than whole-stand models. However, the three approaches were applied for single species (even-aged) stands, and so whole stand models may be preferable to individual-tree models when resources needed for building and application of the models are considerations, in addition to model quality.

In regard to the progress of growth and yield modelling, Moser in Leary (1988) suggested the following historical sequence of development of growth and yield models, namely: (1) yield tables (normal, variable density); (2) yield functions; (3) compatible growth and yield models (even-aged case, uneven-aged case, systems of differential or difference equations); (4) diameter distribution approaches; and (5) simulation approaches (stand models, distance-dependent individual tree models, distance-independent individual tree models).

While growth and yield models for even-aged forests have been developed from all these approaches, from simple yield tables through to the most detailed individual tree distance-dependent models, the development of growth and yield models for tropical rain forests is still in its infancy. Some reasons which might contribute to disproportionate development in growth and yield models in these two distinct forest systems include perhaps: most tropical rain forests reside in developing countries where resources available for this kind of research are limited; tropical rain forest is a complex system where the growth dynamics of many species is still poorly understood, and the concept of growth and yield modelling used for even-aged (single species) is not always applicable to the more complex mixed-species found in tropical rain forests. A few growth models developed for tropical rain forests were either transition matrices (stand level) or individual tree-based distance-independent models using linear (empirical) equations.

2.1.2. Development of even-aged growth modelling

A brief review on the development of modelling growth and yield of even-aged single species stands is given here to try to put into perspective and compare the advances in these models with their uneven-aged mixed-species counterparts, particularly rain forest growth models. Major advances only are mentioned.

Yield tables provided the oldest way for forest growth and yield prediction. The first yield predictions were published in Germany in 1787 (Vanclay, 1994b). In simple yield tables, expected yields were tabulated by age and site index, using information obtained from temporary plots of normal stocking through graphical analysis. Mackinney and Chaiken (1939) have been recognized as the first researchers to use empirical yield equations fitted by linear regression. Schumacher (1939) introduced growth and yield functions, which have been widely used in modelling even-aged stands. Buckman (1962) conducted simultaneous growth and yield modelling for red pine in the Lake States. Clutter (1963) developed a compatible growth and yield model for lobolly pine stands based on the concept adapted from Schumacher (1939) of deriving an algebraic form of yield from mathematical integration of the growth function. This methodology was then improved by Sullivan and Clutter (1972) through developing consistent growth and yield predictions using difference equations derived from the projection equation form of the Schumacher equation.

The Chapman-Richards function (Richards, 1959; Chapman, 1961), known as a generalized form of the Bertalanffy function, and other non-linear asymptotic equations have

been widely used in modelling growth and yield of even-aged stands and other plant growth studies. The advances made and the properties of this family of equations can be found in Pienaar and Turnbull (1973), Nokoe (1978), Causton and Venus (1981), Hunt (1982), Shifley and Brand (1984), Ratkowsky (1990), Zeide (1989, 1990, 1993), Shvets and Zeide (1996).

Diameter distribution models provide more detailed information regarding the stand structure than do whole stand models, which mostly predict stand volume or basal area. The Weibull probability density function has become the most common distribution used for diameter distribution modelling (e.g. Bailey and Dell, 1973; Clutter *et al.*,1983; Kuru, 1989; Villaneuva, 1992).

Cohort models have been used for both plantation and natural mixed-species forests. Cohorts or groups can be formed from trees with similar characteristics: for example, species, size, merchantability. Growth is modelled from the mean tree of each cohort, and for each cohort : identity, mean size and number of stems which can be fractional values, are recorded and updated (Vanclay, 1989). Number of trees within cohorts may be reduced because of mortality, and new cohorts are created when recruitment occurs. Cohort models have been developed for plantation crops: for example, Clutter and Allison (1974) for radiata pine in New Zealand and Alder (1979) for conifers in East Africa, who used equal numbers within classes. Efficiency of this modelling approach, however, depends on the initial formation and management of cohorts (Vanclay, 1989).

Individual tree models have been developed probably since early 1960's. For example: Lemmon and Schumacher (1962), modelled volume and diameter growth of ponderosa pine as a function of size, age, density, and site index. They examined the effect of basal area density of surrounding stands on volume and diameter growth of 557 sample trees (dominant and co-dominant), supplementary to soil-site index correlation. They suggested that overstorey density of surrounding stands (measured by a spherical densiometer), showed significant correlation with volume and diameter growth of the sample trees under investigation. Although this is not directly applicable to tropical rain forest stands, an important implication is the need for finding suitable measures of above ground competition in individual tree-based modelling. Opie (1968) evaluated various competition measures for individual trees of *Eucalyptus spp* in terms of surrounding basal area. He reviewed several methods of expressing competing basal areas: circular plots of constant radius and radius proportional to dbh or subject tree, angle count and angle summation (including and excluding subject tree); and compared them with 'zone count' method (model and field

method). He suggested that the amount of fieldwork and computation needed for each method for maximum precision varied considerably. He recommended the use of zone counts (field method) for estimation of growth and yield, and zone counts (model) if a greater degree of precision is required; for example for studying relative competitive ability of species in mixed-stands. These early ones were hindered by less powerful computing capability than that exist today. With the aid of advanced computing technology, together with the need for more detailed information for management purposes and the desire for better understanding of the behaviour of the system being modelled, individual tree models have emerged as having more potential. Zeide (1989) examined various sigmoid functions (Chapman-Richards, Gompertz, Logistic, Weibull functions, and Power decline 1) for modelling diameter growth of Norway spruce sampled from Guttenberg (1915) data, consisting of 107 dominant trees. The results showed that power decline 1 ($y'/y=at^{-b}$) describe individual tree diameter growth better than the other four functions examined, judged by standard error of estimates. Based on this result, he suggested that the accuracy of the PD 1 indicated that growth is an exponential process, while aging is better described by a power function. Nystrom and Kexi (1997) modelled 5 year individual tree basal area growth of Norway spruce in young stands in Sweden, using distance-dependent and distance-independent models, for 1605 trees sampled from 7025 trees from 595 plots. They found that distance-dependent models using Hegyi's (1974) competition index performed slightly better than distance-independent models (increased in R^2 from 0.77 to 0.79 in models with tree age as a variable, and from 0.74 to 0.76 in models without age variable). The very small difference in performance between these models, indicated no substantial lost of precision by using distance-independent models without the variable age from the one of distance-dependent models with variable age.

2.1.3. Development of mixed-species (uneven-aged) growth modelling

Nelson (1964) stated that '*in recent years, forest mensurationists have successfully characterized the growth functions of pure stands. The development of models to express the growth functions of mixed stands, however, has remained a paradox*'. Twenty years later, the different condition between modelling methodologies for pure and mixed stands seemed to be the same. A similar view to Nelson (1964) was expressed by Leary (1988) in his paper for the IUFRO S 4.01 conference at Minneapolis on forest growth modelling and prediction: he stated '*even though current efforts may be directed at the pure even-aged stand, we should view that as the first step toward representing the mostly mixtures of the real world, and pick our modelling methodology accordingly*'. At this conference, as reported by Adlard *et al.*

(1989), more than 150 papers and posters were submitted; but only 11 papers referred explicitly to tropical forest types. Out of these 11 papers, only 4 had direct application to tropical rain forests, the rest of them were for fast growing plantations. Up to now, growth studies undertaken in tropical rain forests have been mostly for studying the impact of logging on the growth of residual stands and silvicultural treatments for accelerating the growth of regeneration. Among the few growth and yield models developed for these forests, they can be divided into: stand class/cohort models, transition matrices, and individual tree-based models. Another type of model, forest dynamics/gap models, have also been developed for dipterocarp forests (e.g. Bossel and Krieger, 1994).

Development of growth and yield modelling for mixed-species in the tropics is very much behind that for mixed-species in temperate forests. Growth modelling research for tropical rain forests published to date comprises mostly the works of Vanclay for North Queensland forest (e.g Vanclay, 1989a-c, 1991a-d, 1992, 1993, 1994a-b). Since only a few published studies on growth and yield of tropical rain forests could be found, development of growth and yield modelling in temperate forests which have implications for modelling mixed-species in the tropics is also reviewed here.

Nelson (1964) proposed a theory: '*in most cases, on a given site and with comparable stocking, the growth of an even-aged stand of mixed-species composition will not exceed the growth of its fastest growing species in pure stands and will not be less than the growth of its slowest growing species in pure stands*'. While this concept may be applicable for mixture of a few species in temperate forests, it is a much less promising and more tenuous assumption for tropical rain forests, since it requires information on growth of the same species in pure stands which is practically impossible for the large number of species and varied composition of tropical rain forests.

Use of algebraic forms to express growth and yield of stands began in the 1960's (see Clutter 1963). However, since this type of equation was usually expressed as a function of age, it could not be readily applied to uneven-aged or unknown-aged stands. Moser and Hall (1969) recognized this difficulty in applying mathematical integration of growth rate equations as a function of stand age in uneven-aged stands. They proposed the use of a growth equation expressed as a function of a measurable size characteristic of the quantity under investigation. They modelled periodic annual survivor volume and basal area growth rate as a function of average periodic volume and basal area respectively. Solution of the growth rate equation provides a yield function expressed in terms of elapsed time from a

given initial condition, and so this enables the approach to be used for indeterminate aged stands. Lynch and Moser (1986) subsequently proposed a system of differential equations which can be used to construct yield models which provide stand table predictions for mixed-species without involving the variable age. This system consisted of equations to relate stand condition at a particular time (initial conditions) to rate of change in those conditions (number of trees, basal area, and sum of diameters per unit area) for each species group. The solution of these equations was used to obtain the parameters of a two parameter probability density function representing diameter distribution for each species, which could then be used to develop stand table predictions. Input for the simulation using this method can be simple stand attributes obtained from routine forest inventory. Zeide (1993) later demonstrated that a linearized form of exponential decline (ED) function which expressed the decline component proportional to size, was equally successful to the one which is proportional to age when fitted to individual tree data, but less successful when fitted to pooled data and data grouped by site classes. Shvets and Zeide (1996) proposed ED (exponential decline) and PD (power decline) analogies for modelling increment without involving age as a driving variable. Because these methods do not involve the variable age, these allow researchers to entertain their use for characterising ageless stands. Their application, however, has remained largely for even-aged stands. This occurs, perhaps because of the fact that the success of these methods was deem proven, based on only small amount of data or data from stands with simple structures, but the procedure becomes more complex when applied to more mixtures of species which require larger numbers of species groups.

A stand table approach has also been used for tropical forest yield forecasting: for example, Kosgaard (1989) for dipterocarp forest in Sarawak, using the concept of mean time of passage (time for a tree to grow through a diameter class) using de Liocourt's quotient. He modelled several stand tables, each representing species group. Another stand table approach applying de Liocourt's quotient was used by Chai and Sia (1989) for treated logged-over mixed-swamp forest (poisoning of unwanted trees) in Serawak, based on mean growth and mortality rates. The obvious pitfall here was the use of mean growth and mortality rates which did not take into account the fact that both growth and mortality rates vary with size. The method, however, was found useful for straightforward evaluation of different treatments through comparison of the results from stand projection. GHAFOSIM is a stand table projection method developed by Alder (1990) for 'leading desirable' trees of tropical forest in Ghana. The main aim was to provide a tool for forest management within the limitation of available information. Overall, while the stand table approach has been demonstrated as a

useful tool to describe development of forest stands, its application may be complicated when dealing with many species groups, which need to employ several tables of movement ratios for different species groups, with additional tables for mortality and recruitment, and more so, if it has to be adjusted with different stand densities (see Vanclay, 1994b).

Matrix models are also widely used in modelling uneven-aged stands. Bungiorno and Michie (1980) developed a matrix model for North-Central region hardwoods (USA), based on Leslie's and Lewi's growth model (Lewis, 1942; Leslie, 1945, 1948). Mendoza and Setyarso (1986) adapted the Buongiorno and Michie's (1980) approach for evaluating the capability of the Indonesian selection cutting system to sustain future harvests, and alternative harvesting schemes, using 1 and 2 year growth data from logged-over tropical rain forest in Central Kalimantan, Indonesia, with 35 and 45 years projection length. Ingrowth was assumed constant for each time step. They suggested that the current silvicultural prescription using a minimum of 50 cm diameter should be cut, leaving 25 commercial trees per ha (with dbhob = 20–49 cm), and with a 35 year cutting cycle will not be able to sustain the current level of harvest after the second cutting cycle. They also offered alternative harvesting schemes based on different cutting cycle or proportion of growing stock. Another matrix model for tropical rain forest in Indonesia was developed by Suhendang *et al.* (1995) using a Leslie matrix, to determine annual allowable cut based on the number of trees per diameter class. The stands were classed into 6 different site conditions based on volume per ha before being logged (primary forest condition) for all tree species of 10 cm diameter or greater. The model provides projection of future stand structure for all species together, and dipterocarps and commercial non-dipterocarps by 10 cm diameter classes, which can be used to determine annual allowable cut based on the number of trees in each class, as well as to estimate recoverable volume per diameter class for each species group. Limitations of these approaches are that the probability of events (trees stay or move to the next class) do not change overtime, and that competition cannot be accommodated readily, while ingrowth cannot be varied (see Vanclay, 1989).

Stand table projections and matrix methods encounter several limitations, but cohort models offer more flexibility, as they enable projections to be made under a wide range of conditions and provide diverse information for reporting (see Vanclay, 1994b). Cohort models for mixed-species have been developed for both temperate forests (e.g. Leary and Holdaway, 1979) and tropical rain forests (e.g. Vanclay, 1989a; Alder, 1995). Leary and Holdaway (1979) predicted the sum of diameter increment for each cohort as a function of potential diameter increment per tree, number of trees in the cohort, and adjusted by stand

density and competition. Vanclay (1989a) developed cohort models for north Queensland rainforests, using cohorts with many stems for non-commercial species and non-merchantable sizes; and which allowed cohorts to be split when commercial stems reach merchantable sizes. Mortality and harvesting were accommodated by merging cohorts, while recruitment was modelled through forming new cohorts. This model was the basis for later development of the NORM (tree list) model (see Vanclay, 1994b). A cohort model for a tropical forest in Brazil (CAFOGROM) was developed by Alder (1995). The CAFOGROM provided user interface which enable the users to simulate different harvesting and thinning options, with graphical output displaying basal area per diameter class, volume over time, and basal area components. He suggested that the results showed conformity with approximate expected productivity of tropical mixed-species found in other reported data.

Several individual tree models have been developed for mixed species in temperate as well as in tropical rain forests. Individual tree models developed for temperate forests include examples set out in the two paragraphs below.

Distance-dependent models : A 10 year tree basal area growth for uneven-aged hardwoods in Southern Illinois was modelled by Moore *et al.* (1973), using modified area potentially available (APA) as a competition index as compared to the competition influence-zone overlap (CIO) advocated by Bella (1971). Individual tree growth was predicted as a function of dbh, total height, crown surface area, age of the subject tree, and competition index. Neither competition index showed much different contribution to the response variable. Because of the predictor variables involved in this approach, it is of limited use for tropical rain forest applications. Ek and Monserud (1979) examined the performance of stand growth models based on individual tree (FOREST) and diameter-class growth models (SHAF) for describing changes in stand density and structure of Northern hardwoods stands. They suggested that the use of the two models will be determined by objective and operational constraints. FOREST appeared to be more suitable for development of management guides and analysis of silvicultural alternatives in detail, while SHAF was probably best applied for short-term inventory projection. Biging and Dobbertin (1995) evaluated various distance-dependent and distance-independent competition indices in terms of variation in height and the square of diameter growth of individual conifer trees which can be explained by both types of competition index, for mixed-conifers in Northern California. They found that distance-independent competition with crown measures (CCp = crown cross-sectional area, CVp = crown volume, and CSAp = crown surface area) performed slightly better than the best distance-dependent competition indices from Biging and Dobbertin (1992), judged by the

reduction in mean square error (MSE). This outcome provided a useful guide to exploring various expressions of competition factors for modelling tropical rain forest trees.

Distance-independent models: A basal area increment model for individual conifers in the Northern Rocky Mountain region was developed by Wykoff (1990), using quadratic function which included site factors such as habitat type, location, elevation, and a combined effect of aspect and slope, as well as competition factors. This model was developed from an extensive data-base and has been the basis for many individual tree models for mixed species. A similar approach was adopted by Monserud and Sterba (1996) for mixed-species in Austria, with their more detailed investigation on the effect of site characteristics, such as depth of F and H humus horizons, and dummy variables for soil depth, soil moisture, slope position, soil group, vegetation type, and growth district. They found performance of this model was similar to Wykoff (1990) model despite the differences in the way increment data were obtained. Wykoff's (1990) data were obtained from increment borings, while Monserud and Sterba's (1996) data came from successive re-measurements. Uzoh *et al.* (1997) predicted diameter increment of understorey trees following overstorey removal in mixed-conifer stands in six study areas of Northern California. They found that there was no significant difference in periodic annual diameter increment of residual trees between 8 and 10 years before, and 8 and 10 years after overstorey removals. The increase of periodic annual diameter increment in residual trees was found substantial for 9 to 16 years after overstorey removals. Shafii *et al.* (1990) developed individual tree diameter increment models of mixed-conifers receiving different treatments (fertilized, thinned, fertilized and thinned, and untreated). Diameter (inside bark) growth was constructed for growth periods of 5, 10, and 15 years based on the growth periods after treatment. The logarithm of squared diameter growth was predicted as a function of ln (dbh), initial stand basal area, relative dbh (dbh of the subject tree divided by average stand diameter), individual tree percent live crown, crown competition factor of trees larger than the subject tree, and dummy variables representing habitat type, treatment, species, slope, aspect, and elevation. The model was found to perform well in several independent data sets. All of these models were fitted using linear regression, and had some similarity in terms of predictor variables used in the equations. Because of the flexibility in accommodating stand attributes, locality factors, and competition, which can be adjusted according to available information, and the simplicity in the equation fitting procedure, this approach has also been used in individual tree models for tropical rain forests.

Development of individual tree models for tropical rain forests probably started early in the 1980's. Among the few individual tree models developed for tropical rain forests, only

the North Queensland growth model has been improved several times using a large data base covering long periods of re-measurement and various stand conditions (see Vanclay, 1989a, 1989c, 1991b, 1991d, 1994b). Wan Razali and Rustagi (1988), and Ong and Kleine (1996) modelled diameter and basal area increment respectively, for dipterocarp forests in Serawak. The Wan Razali and Rustagi (1988) model was developed based on very limited information, and that the variables included in the models limit the application of this model (e.g. the use of lagged variables : annual tree basal area growth rate and total annual basal area growth of all species per plot during the previous measurement period). The Ong and Kleine (1996) basal area increment model was part of DIPSIM (Dipterocarp forest growth simulation model), developed from 31 plots totalling 31 ha in area, which were established in the early 1970's. The DIPSIM can be used to determine desired growing stock level and annual allowable cut based on a desired future growing stock, as well as modelling growth of the forest under various harvest levels. The model, however, has not been tested with independent data. Two model components (mortality and recruitment) have not been able to be developed satisfactorily, and so mortality rates based on long-term research plots were used, while recruitment was expressed as the annual (average) recruitment rate for each species group. Pambudhi (1997) modelled tree basal area growth (for about 2 years of growth period) of a logged over tropical rain forest in Indonesia, one and five years after logging (at the first measurement), covering 54 plots, each of 0.1 ha area. He examined distance-dependent and distance-independent competition factors (stand density, stand basal area, and stand basal area greater than the subject tree) for four species groups. He found that distance-dependent competition factors did not perform much better than distance-independent ones, despite more complicated procedures in obtaining the variables needed and in calculating the competition factors. Maximum improvement of only 3.5 % in R^2 was obtained for the Group 'commercial non-dipterocarps' through replacing stand basal area with competitive influence zone overlap. When crown form and crown position were included in the model, these measures explained a minimum of 3 % of the variation for the Group *Shorea*, and a maximum of 10 % for the Group 'other dipterocarps'. Pambudhi (1997) suggested that crown form is more difficult to assess in the field and to interpret than crown position. The use of a model with crown position, however, should be restricted for short predictions unless a measure for its adjustment is available.

The development of growth and yield modelling for uneven-aged mixed-species stands seems to be divided between stand level, and individual tree level both distance-dependent and distance-independent. Individual tree level modelling using linear models has

been widely used for mixed-species both in temperate and tropical rain forests during the past two decades. Several studies on evaluating various competition factors for individual tree level modelling have been done in temperate forests. They have provided useful guides, apparently, to exploring possible competition measures suitable for tropical rain forest condition. The main constraint in modelling growth and yield of tropical rain forests at present is the lack of data coverage in terms of area (various site and stand conditions) and measurements period.

2.2. THE TROPICAL RAIN FOREST SYSTEM

2.2.1. Tropical rain forests in general

According to Whitmore (1975), *tropical rain forest* is a term introduced by A.F.W. Schimper in his classic work *Plant geography*, published in 1898 and 1903. The term refers to the forest of the ever-wet tropics where there is no or only a minimal seasonal water shortage.

There are three large blocks of tropical rain forest in the world (Whitmore, 1975; Bruenig, 1996). The largest block is in the Amazon basin together with other Latin America and Caribbean rain forests; Indo-Malayan (Asia-Pacific rain forest) is the second largest block, while the Congo basin (African rain forest) is the least extensive block of remaining tropical rain forest. The distribution of the three blocks of tropical rain forest can be seen in Figure 2.1 (redrawn from Whitmore, 1984).

There are similarities in the structure of the various kinds of rain forest and physiognomy of the species in all three blocks, but the species themselves are entirely different. The Indo-Malayan (Asia-Pacific) forests, also termed *tropical rain forest of the far east* by Whitmore (1975), are known to have the most eminent structure and greatest richness both in plant and animal life, compared with the Amazonian and African rain forests. The tropical rain forest of the far east can be divided into the following formation:

1. tropical lowland evergreen rain forest (up to 1200 m above sea level),
2. tropical montane rain forest (1200 – 3000 m above sea level),
3. tropical sub-alpine forest (>3000 m above sea level),
4. heath forest,
5. forest over limestone and ultra basic rocks,

6. beach vegetation,
7. mangrove forest,
8. brackish-water forest,
9. peat, fresh water and seasonal swamp forest,
10. tropical semi-evergreen rain forest.

(from van Steenis, 1950b in Whitmore, 1975).

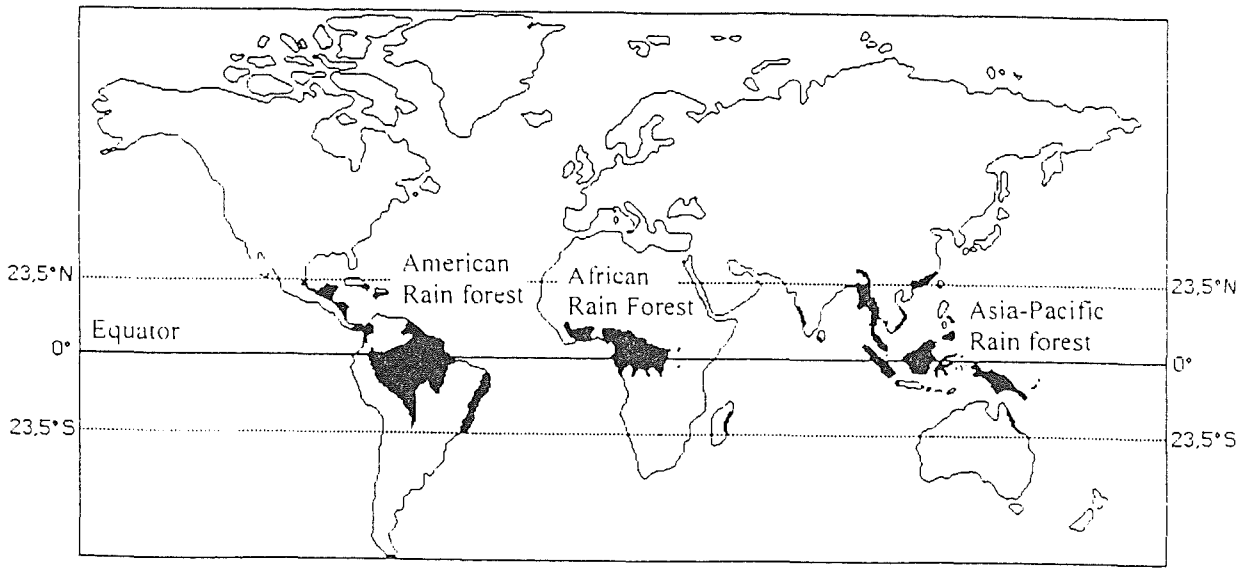


Figure 2.1. Distribution of tropical rain forests (redrawn from Whitmore, 1984)

Within the Indo-Malayan (Asia-Pacific) rain forest, there is a great variation in flora (Whitmore, 1975). The most obvious variation is a major difference between the western and eastern blocks. The western block is dominated by *Dipterocarpaceae* family in the top canopy, and the forest has greater height than any other broad-leaf tropical rain forests in the world. *Dipterocarpaceae* is the giant and dominant family of the South-East Asia's forest (Carter, 1984), which provide good quality timber (Kessler, 1996). Dipterocarp species have great variation in growth rates : a number of them are shade intolerant species which show rapid growth rates and reach mature phase within 60 years, while others are shade bearers which grow very slowly (Ashton, 1982). He further suggested that the intolerant dipterocarps perhaps have life span of 250 years, while the shade bearer dipterocarps may exceed 1000 years, judged on girth growth data. From PT. ITCI data used in this study for example, average diameter increment per 1 cm diameter class > 0.8 cm/year was found for some *Shorea* species, compared to 0.2 and 0.3 cm/year for *Vatica oblongifolia* and *Dipterocarpus tempehes* respectively. It suggested that for the purpose of growth and yield modelling, when species aggregation is considered, the dipterocarps need to be dis-aggregated in some way in

order to minimize the possibility of over or under predicting for some species. For management practice, it can be a guide for silvicultural treatment, especially related to liberation practice for young trees following logging, as well as the selection of desirable tree species for the next cutting cycle.

2.2.2. Tropical rain forests in Indonesia

The family *Dipterocarpaceae* is predominant throughout the lowland evergreen rain forest in Indonesia. The dipterocarp species are commercially important, and their management in the rain forest has been emphasized for the past decades.

Sidiyasa *et al.* (1990) identified nine genera and more than 250 species of *Dipterocarpaceae*, found in Kalimantan. Among the nine genera, *Anisopthera, Cotylelobium, Dipterocarpus, Dryobalanops, Hopea, Parashorea, Shorea, Upuna*, and *Vatica, Shorea* was found to show the highest species richness (133 species), followed by *Hopea, Dipterocarpus*, and *Vatica* each of 44, 41, and 35 species respectively; while other genera were found to have only relatively few species. While most *Dipterocarpaceae* dominate the top layer, most species of the genera *Hopea* and *Vatica* never reach the forest canopy level. *Dipterocarpaceae* grow in peat swamp forests up to high altitude forests. Some *Shorea* grow naturally together with other species, for example : *Shorea balangeran, Shorea leprosula,* and *Shorea compressa,* with *Lophopetalum javanicum* in swamp forest (Soemaryono, 1996); *Shorea platyclados, Shorea tripinata,* and *Shorea curtisii*, with *Agathis borneensis* in high land forest of East Kalimantan (Bratawijaya in Soemaryono, 1996).

Non-dipterocarp species in Borneo comprise approximately 100 families, 360 genera, and amount perhaps to more than 2000 species (Kessler, 1996). The non-dipterocarp species mostly occupy understory layers, only a few of them reach the top canopy: for example, *Dialium, Koompassia, Sindora* (Caesalpinaceae), and *Dyera costulata* (Apocynaceae).

The understory layers composed mostly of *Annonaceae, Euphorbiaceae, Lauraceae, Meliaceae, Myristicaceae, Myrtaceae*, and *Rubiaceae*. Kessler (1996) divided the non-dipterocarps into commercial timber tree species, ecologically important tree species, fruit trees, and lesser known timber tree species. Some genera in non-dipterocarp families have high species richness: for example, the genus *Eugenia* alone is estimated to have at least 300 species in Borneo; and the family *Rubiaceae* has at least 250 species of woody plants which do not grow more than 10 m in height.

Characteristics of many species, genus, or family comprising the dipterocarp forests, are still very little known. Moreover, associations between species in particular site conditions have been found. These two aspects suggested that there is a need to change the management of dipterocarps forest from concentrating on commercial species (largely dipterocarps), to take into account the importance of other species from other points of view than consideration of commercial values only. The implication for growth and yield studies, then, is that there is a need to identify ways of grouping species to reflect growth characteristics, rather than based only on commercial consideration. Modelling techniques which enable species identity to be preserved have been well developed, which enables information for management purpose with different level of detail to be provided.

2.3. SOME ASPECTS OF MODELLING TROPICAL RAIN FORESTS GROWTH

2.3.1. Modelling options

Forest conditions being modelled, the individual purpose of building models, and resources available to build and apply the models are all factors likely determine the choice of kinds of model to be built and approaches to be used. Growth and yield models developed for tropical rain forests during the past two decades can be divided into : (1) size class (stand table approach, transition matrix and cohort models); and (2) individual tree models (empirical equation approach). While this review emphasizes growth and yield models, gap models are also outlined in order to cover optional approaches available for modelling tropical rain forests for different purposes, forest conditions, and other factors. Other methodologies used for uneven-aged temperate forests, which are related to the objectives of this study are also reviewed.

Modelling growth and yield of tropical rain forests is known to be more difficult than that for uniform plantation forests, because of : (1) the large number of species which contribute to their stand structure and forest dynamics (Adlard *et al.* 1989, Wan Razali 1989); (2) species identification posing difficulties; and (3) measurement of girth or diameter having to be shifted upwards because of buttresses/irregularities. Other measures on which plantation forest modelling mostly depend but which create difficulties in natural forests, include: (1) age being indeterminate; (2) measurement of height and crown properties, especially in dense canopies, being error-prone; and (3) simple site indicators not being readily available.

Vanclay (1994b) described differences between models for growth and yield in uneven-aged forests. Models which express the status of forest at some future time are named yield models, and ones which express increment are growth models. In regard to the nature of growth models, Bruce and Wensel (1988) stated that '*the greatest difference among growth models is in regularity of the stand. Irregular stand models require detailed description of individual trees and are seldom successfully simulated by simple models developed for regular stands*'.

Adlard (1995), expressed the view that the purpose of modelling growth in forestry should include: growth estimation for yield prediction, health monitoring, long term productivity monitoring, and socio-economic analysis of forest influences. However, the nature of many data available to date has perhaps led growth modelling efforts to emphasize only on yield prediction. Dixon *et al.* (1990) pointed out three components necessary for building models, namely: (1) an understanding of the process or relationships being modeled; (2) mathematical, statistical, and computational techniques; and (3) experimental or survey data. Unlike in many short term investigations where researchers are able to plan and design the experiments to suit the objectives of the research, researchers in forest growth modelling often encounter difficulty where the approach of modelling has to be adjusted to the information already at hand.

Important choices in modelling philosophy would still be between stand level and individual tree models, and between deterministic and stochastic models (Adlard, 1995). In regard to tropical rain forest growth modelling, Bruenig (1996) viewed that the existing conventional yield tables based on simple or multiple linear regression, and stand table projection models, cannot cope with heterogeneity of sites and forests satisfactorily, as well as with the variability of growth dynamics of trees. The objective of building a model, together with the degree of precision expected and resources available to build the models, however, will always direct the choice of modelling approach. In the case of tropical rain forests, it has been found in a number of studies that crown measures are important factor affecting tree growth (diameter or basal area). The crucial questions are: what the model is going to be used for?, how easy can these variables be measured in the field and interpreted or calculated?, are these measures readily available in routine inventory data?, how much precision is lost by excluding any of these measures?, or how much has to be spent on collecting and calculating these additional measures to achieve certain improvements in precision?.

Growth of a tree is an individual stem character which is controlled individually by phenotype, individual status and characteristics, local history and environmental factors (Sheil, 1995). Species perform differently on different sites, and from place to place within a site, which may be associated with variations in soil, inherent genetic variability, variation in crown size and exposure (Whitmore, 1975). Trees in the aseasonal evergreen tropical rainforest exhibit marked rhythms of stem growth (diameter or basal area growth) which vary greatly between trees of the same species within a community, between different radii within one stem, and between species, in a manner which is difficult to explain. Individual tree modeling, is therefore, probably the most suitable approach to capture these variations.

2.3.2. The need for grouping species

Tropical rain forests are known to comprise a large number of species but many of them are represented by only a few trees. Their growth rates vary greatly, and so it is unlikely that one model can be developed for all species. Conversely, it is not possible, at least at this stage, to develop one model for each species. Species need to be grouped using criteria which appropriately reflect the intended use of the model being built, and also take cognisance of the data available for building the model.

Vanclay (1994b) divided ways of species grouping into : subjective grouping, for example using economic or ecological criteria; and objective grouping using numerical analysis. An example of species grouping based on ecological criteria was proposed by Swaine and Whitmore (1988). They divided tree species into pioneer and climax species, each was further divided based on height at maturity (pygmy, small, medium, and large). There are relatively few publications on modelling mixed species with species aggregation using an objective grouping basis (e.g. Meldahl *et al.*,1985; Leach *et al*,.1991; Vanclay, 1991b; and Alder, 1995). The resulting groups, however, may also be data or functional form dependent (see Vanclay, 1991b, 1994b). Among growth studies undertaken for dipterocarp forests, researchers tended to separate species on the basis of dipterocarps and non-dipterocarps, or commercials and non-commercials. For example: Wan Razali and Rustagi (1988), Wan Razali (1989), Ong and Kleine (1996), and Pambudhi (1997), which were related directly with growth modelling; while Nguyen-The *et al.* (1996) observed growth of residual stands for a few years following logging activities. The tendency to separate dipterocarps from non-dipterocarps or between commercial and non-commercial species may

be suitable for the intended use of the model, but the great variability in growth rates (as described earlier in this chapter) between species of dipterocarps may be overlooked.

2.3.3. Individual tree based distance-independent modelling: the approach used in this study

Distance-independent models are those which are based on a vector of diameters or diameter classes, but for which the competitive status of each tree or class does not require positional information of the trees (Munro, 1970). They require at least some individual tree information for the explanatory variables (Clutter *et al.*, 1983). These models assume, therefore, a close correlation between trees, and stand variables and tree competitive status.

Unlike distance-dependent models, there is no general form which has been followed in the construction of individual tree distance-independent models (Daniel and Burkhart, 1988). Distance-dependent models which have been developed, generally share a common structure although they do vary in detail. Distance-independent models simulate growth individually, usually as a function of current size and stand attributes. Detailed tree records are maintained for these models, providing a great deal of information on stand structure. For distance-dependent models, initial tree and stand attributes are input or generated and each tree is assigned a coordinate location. The growth of each tree is simulated as a function of its size, site quality, and a measure of competition from neighbours.

A major difference between distance-dependent and distance-independent models is in expressions of tree competitive status. For irregular stands, no single measure of stand density will serve to represent the competition affecting individual trees (Bruce and Wensel, 1988). This problem can be resolved by subdividing the stand and measuring local density. From a theoretical point of view, they argued, the best solution may be to use a distance-dependent model where the size, vigour, and proximity of neighboring trees are evaluated. These models have been developed towards more biologically realistic process models (Adlard *et al.*, 1989; Bossel and Krieger, 1994). They can be expected to be an important guide for policy evaluation for forest management in relation with a changing environment, while growth and yield models will continue to provide information on forest growth central to forest management and research purposes (Mohren and Burkhart, 1994).

Empirical equations (multiple linear regression) have been widely used in modelling growth of uneven-aged forest stands (eg. Wan Razali and Rustagi, 1988; Vanclay 1991b, Ong

and Kleine, 1996; Monserud and Sterba, 1996; Shafii *et al.,* 1990; Pambudhi, 1997, Uzoh *et al.,* 1997). A modified beta function was also used by Vanclay (1989a) for modelling diameter increment of tropical rain forests in North-Queensland; then by Alder (1995) for modelling basal area increment of *Piptadeniastrum africanum,* grown in mixed-species forest in Ghana. Some researchers have demonstrated the potential of probabilistic functions for individual tree based modelling, particularly for modelling mortality (for example : Buchman, 1979; Hamilton, 1974, 1986, 1990; Monserud, 1976; Ong and Kleine, 1996; Vanclay, 1989a, 1991c, 1994a; Wan Razali, 1988, 1989), and recruitment and or regeneration (Vanclay, 1989a, 1992). Vanclay (1991d, 1994a) used this function for modelling diameter growth of North Queensland rain forest. He stated that this model had some advantages, it provided robust estimate despite outliers in the data and simplified the construction of a compatible deterministic-stochastic model.

Some researchers have attempted to use sigmoid functions in growth (differential) form without variable ages: for example, Moser and Hall (1969), Lynch and Moser (1986); Zeide (1993); and Shvets and Zeide (1996). The applicability of these approaches to individual tree based modelling of tropical rain forests as described earlier in this chapter, however, still needs to be studied. A sigmoid type function, 'Gompertz function', has been demonstrated to perform well for plant growth studies by some authors. Causton and Venus (1981) stated that 'the Gompertz function has been found to be more appropriate in biological work than any other sigmoid function'. Ratkowsky (1990) described the Gompertz function as one of versatile and useful three parameter curves with an inflection point, that it has the property of close-to-linear which is a prerequisite for the appropriateness of using the least-squares method for parameter estimation. Although applications of the Gompertz function in plant growth have been mostly for individual organs (leaves in particular) (Hunt, 1982), he also indicated the reasonableness of this function for modelling the growth of whole plants. Huang and Titus (1995) developed an individual tree diameter increment model for spruce grown in mixed-species stands in Alberta, using the two parameter Box-Lucas function. The data used came from 164 PSPs in the region, which had been measured up to 5 times. The two parameters were expressed as linear functions: one as a function of basal area per hectare of all species in the stand, proportion of spruce to total stand expressed as basal area per hectare, tree height, relative diameter, and spruce site productivity index; while the other parameter was a function of the square root of total number of trees per hectare. Interval length between measurements was added to the basic form. The equation was fitted using ordinary non-linear least-squares (NLS), NLS with first order autoregressive (AR (1)) errors,

and NLS with AR (1) errors weighted by reciprocal of square diameter. The ordinary NLS resulted in non-homogenous residual pattern, a typical pattern when fitting increment functions without transformation. The weighted NLS with AR (1) error improved the residual pattern. Evaluation with independent data showed that the mean prediction bias was not significantly different from zero. Because the response variable was expressed as periodic diameter increment and accommodated the interval length as a predictor variable, this equation may have the potential to be used for data with any interval length of re-measurements. The limitation of this model perhaps is the complex procedure in parameter estimation.

Despite the criticism relating to possible pitfalls in using linear (multiple regression) models, this form of model remains in use even in this computer age when computational difficulties no longer need to be a constraint to fitting other forms. The use of linear models for individual tree based modelling during the 1990's can be found in a number of publications. A few examples would include: Vanclay (1991b), Alder (1995), Monserud and Sterba (1996), Ong and Kleine (1996), Pambudhi (1997), Uzoh *et al.*(1997).The fact that the procedure for fitting non-linear models to data is more complicated than for linear models, might have been the reason for the extensive use of linear equations for individual tree based modelling growth for tropical rain forests as well as for sub-tropical forests.

The choice between using non-linear or linear equations is also influenced perhaps by the fact that both types of equation have their merits and inadequacies. Non-linear equations are recognised as being more flexible for extrapolation outside the range of data than linear equations, but they do not necessarily provide a unique best unbiased solution for a given set of variables (Ratkowsky, 1990; Vanclay, 1994b). Furthermore, starting values and iterative methods used also affect the solutions. Linear equations are fitted using much simpler procedures than non-linear equations, and careful selection of variables to be included in the model will give reasonable predictions within the range of data used to build the model. However, linear models should not be extrapolated beyond the ranges of the data used to build it. Another problem is computational difficulties when variables included in the model are closely interrelated (multicollinear); precision of calculation between components will be rapidly lost if those components are highly correlated (UOR, 1994).

2.3.3.1. Variables included in the models

Much modelling of tree growth relies heavily on field measurement of stem diameter at breast height for the following reasons (Zeide, 1989): stem diameter is the easiest tree dimension to measure and monitor, it is sensitive to environmental changes (see also Botkin, 1993), as well as to stand density; it is related closely to crown size, tree mass, or stem volume; and in temperate climates, it is constantly recorded by annual layers, which greatly facilitates data collection. Dawkins (1963b) found that there is a linear relationship between crown and bole diameters for most tropical tree species. This relationship can be used as the basis for calculating stand density which can be accommodated per unit area (e.g. per ha) to enable trees to have good crown growth. It also facilitates expression of competition based on tree diameter.

Most individual tree distance-independent models for uneven-aged stands have been developed using empirical equations (multiple linear regression), expressed in the form of diameter or basal area increment as a function of current size (diameter or basal area), stand attributes to express competition, and a measure of site quality. Basal area has also been used as the best measure available of the soil volume exploited (Dawkins, 1963b). For a particular species of a defined age on a given site, basal area indicates the extent to which the available area have been utilized (Loetsch and Zöhrer, 1973), which can be an indication of the degree of competition for below ground resources.

Vanclay (1989a) acknowledged that relative dominance and/or crown class provides a good indication of growth potential for mixed forests, and can probably be included in increment functions. However, crown measurement in tropical rain forests is error prone, and it is perhaps also impractical to consider such measurements in routine inventory. Variables which are commonly used in individual tree models for uneven-aged stands: for example, species, diameter (d), stand basal area (G), estimate of site productivity, and basal area greater than the subject tree ($G_{>d}$).

Enright and Hartshorn (1981) stated that in trees, competition between individuals (from the same and from different species) for light and nutrients is a major determinant of their growth rate and ultimate reproductive success. Panayotou and Ashton (1992) found that, among a number of environmental factors affecting tree growth, light is perhaps of greatest interest to forest managers, owing to the relative ease of its manipulation through silvicultural treatment. Sutisna (1994) experimented with four degrees of liberation in logged over

dipterocarp forest in East Kalimantan; and found that among the growth factors of the forest trees in natural forests, such as temperature, soil depth, water, nutrient availability, space, and light, only space and light are the factors limiting tree growth. The effect of this silvicultural treatment can probably be accommodated in growth model by including discrete variables reflecting types of silvicultural treatment and/or combined with years since the treatment.

2.3.3.2. Measures of competition and site quality

Competition exists if resources available to individual trees are reduced and development of the individual is modified by the presence of other individuals in the population (Curtis, 1970). Hence, for an organism of fixed size and requirements, intensity of competition varies with density expressed as the number of individuals. In forest stands, definition of density as the number of individuals per unit area is of limited usefulness, because trees increase in size more or less indefinitely; and also change in dimension and ability to utilize available site resources in response to the influence of adjacent trees. Alternatively, basal area can be used, being frequently as a measure of stand density. Its widespread use as a stand statistic probably originated from its use as one of the three factors in computation of volume (basal area, height, and form) rather than from biological interpretation. Other than stand basal area (G) and stand basal area greater than the subject tree ($G_{>d}$), stand basal area excluding the subject tree (G-g) has also been used as a measure of competition (e.g. Ong and Kleine, 1996), as well as tree competition index ($1-G_{>d}/G$) (Alder, 1995), and relative size ($G_{>d}/\ln(d+1)$) (Wykoff, 1980). The variable $G_{>d}$ is used in the subtropis (e.g. Wykoff, 1990; Monserud and Sterba, 1996) as well in the tropis (Vanclay, 1989a; 1991b; Ong and Kleine, 1996). The JABOWA (Botkin, 1993) model implied an assumption that leaf area is proportional to the square of tree diameter; shading leaf area (Ach) is the sum of leaf areas on taller trees. Tree height is assumed to increase monotonically with diameter, so shading leaf area is analogous to $G_{>d}$, depending on the specific height-diameter relationship.

Briegleb (1952) pointed out that the ability of a tree to utilize growing space depends not only on stem diameter but also on crown development, which is determined by the previous history of the stand. Crown related variables, such as crown ratio and crown competition factor, have been used for modelling individual tree growth of mixed-species in temperate forests (e.g. Wykoff and Monserud, 1988; Biging and Dobbertin, 1995, Monserud and Sterba, 1996). Biging and Dobbertin (1995) compared 9 distance-independent crown

related competition factors to the best distance-dependent competition index they obtained in Biging and Dobbertin 's (1992) model. They found in this comparison that 3 distance-independent competition factors, namely CC_P (crown closure), CV_p (crown volume), CS_p (crown surface area) performed better than the distance-dependent competition factor tested. These three variables require information on tree height to the crown base, which may not be feasible to ascertain in tropical rain forests from a practical point of view.

Bruce and Wensel (1988) argued that relationships among trees are not so simple as to be defined completely by the description of neighboring trees and distance to them. Because of localized genetic similarity, stand histories, and root-grafts, not all trees grow independently. Also, roots capture unoccupied space faster than branches (Smith, 1986). Sometimes, competition in sites with low water-holding capacity and in areas with low rainfall, is as important as crown competition in affecting tree growth. Consequently, there are places where stem size and stocking level are more effective than complicated measures of crown related factors in examining competition for empirical growth models. Distance-dependent competition factors may be useful for research purposes, but cannot often be used in growth models for forest management because the necessary spatial data are rarely available from operational inventory.

Wykoff and Monserud (1988) compared site index, habitat type and abiotic site descriptors (elevation, slope, aspect, and location) as means of expressing site productivity effects, by fitting separate diameter increment models to Douglas-fir for Northern Rocky Mountains data. They found that the models behaved similarly. The effect of crown competition factor (CCF) was not apparent, a correlation between site and density was suspected (good site should be able to support more biomass than poor sites). Monserud and Sterba (1996) expressed site factor as a function of : topography (elevation, slope, azimuth, position on the slope), soil (soil depth, soil group, thickness of humus horizons), vegetation (vegetation and soil moisture), and geographic variables (growth districts); they found that the site factor explained at the most 6 percent of the variation. They also examined the effect of crown competition factor (CCF), and suggested that CCF had only a minor contribution to the response variable.

Growth measured from permanent plots reflects confounded effects of site potential, density, and species composition (Moser and Hall, 1969). Site index and soil characteristics have been used as site quality variables in growth functions for uneven-aged stands (Ralston, 1964 according to Moser and Hall, 1969), but results are inconclusive. Vanclay's (1989a)

models included soil quality and soil parent material as measures of site, expressed as dummy variables; and include time since silvicultural treatment in his later modelling (Vanclay, 1991b). Botkin (1993) stated that location of a site in relation to altitude, slope, and aspect can represent important factors affecting growth, as these affect temperature, precipitation, and soil characteristics (soil depth, average soil particle size, and percentage of rock in the soil), all of which influence the availability of moisture. Wykoff (1990) included environmental factors such as : habitat type, location, altitude, slope and aspect

Bruenig (1996) stated that rain forest soils are extremely heterogeneous and their taxonomy is confusing. The soils in rain forests can vary profoundly at a scale of a few square metres to square hectares according to the spatial variation of the geological substrate, geomorphology, climate and long-term influences of vegetation. Influence of vegetation on soils was also found by Willis *et al.* (1997) in northeastern Hungary. Results of his study suggested that deciduous trees increased on podzolic post-glacial soils, and that increase was one of triggering mechanism contributing to the development of brown-earth soils. A soil study in PT. ITCI growth plots conducted by Bremen *et.al.*(1990) found higher nutrient levels in the A horizons in most profiles located in the 5 logged plots than in other plots. They indicated difficulties to relate them with differences in soil parent materials because nutrient contents in lower horizons were not clearly higher than for the other plots. They suspected that different composition of vegetation between logged and unlogged plots resulted in the differences in composition of organic matter in the A horizons. All of these suggested the need for monitoring the changes in vegetation composition and soil conditions in long-term forest growth studies.

Primack *et al.* (1989) reported that, in their 15 years of observing growth of dipterocarps in primary forests and logged forest (with improvement felling), there was no clear relationship between soil fertility and growth rate. It perhaps because the location with better soil fertility has steep topography, higher stand density and higher canopy; while another location, although less fertile, had better terrain and also less competition because stands comprised mostly young trees. They also found that there was no apparent difference in tree growth rates in the primary forests and in forest given improvement felling, which may have been due to differences in species composition and initial size distribution between these two forest conditions. These two cases indicated the problem of direct comparison of observations, unless other factors such as species and size composition, as well as site conditions are taken into account.

Vanclay (1994b) pointed out that in order to provide reliable data for growth modelling, tree measurement prerequisites for permanent plots include the following: individual tree identification should not be ambiguous, the plots should be homogenous and sample the whole range of stand conditions. However, in some cases, growth data cover only small ranges of stand condition, which may also contribute to confounding effects between variables.

2.3.4. Implications for the research reported here

The research findings reviewed in the above section indicated the complexity in determining the most suitable measures of competition and expression of site characteristics central to individual tree-based modelling. Based on research finding so far, distance-dependent models have not proved able to give considerable improvement to individual tree models despite the complexity in deriving them. And so, distance-independent models seem to be preferable to distance-dependent ones for modelling mixed-species forests. Furthermore, a distance-independent model is more suitable in providing information for forest management with selection cutting system than other types of model such as stand level models.

Sustainable management of a complex forest system (e.g. tropical rain forests) requires growth models which are able to provide information for predicting future stand structure (species and size distribution), as well as production capability for different sites and or stand conditions.

Increasing international concern about tropical rain forest management, and the decrease in potential of natural forests for timber production as a result of changes of forest conditions (from primary to secondary forests) require more careful planning and management of this forest, while changing from concentrating on dipterocarp species only to also taking into account other species which are either potentially commercial or ecologically important seem desirable. The implication is that the assumption of average diameter growth of 1 cm per year for dipterocarps as the basis to determine the cutting cycle in Indonesian selection cutting systems can no longer be retained. Models which can provide information on growth of individual species or species groups will be more reliable to determine silvicultural prescriptions in a selection cutting system than those based on assumed growth rates. Individual tree-based models which retain species identity are more suitable for this purpose. Species grouping (which is needed for modelling this type of forest), should be based more on

growth characteristics than based on commercial criteria which has been commonly used to date for grouping species of dipterocarp forests.

Methodology used in developing individual tree-based models in temperate as well as in other tropical rain forests can be adapted for forests in East Kalimantan. Most individual tree-based models have been developed using linear (empirical) equations. Although this approach provides reasonable fit within the range of the data and use simple procedure in fitting the models, as has been stated earlier in this chapter, it has obvious drawbacks. Asymptotic non-linear equations are known to have more biological realism than ones based on linear (empirical) models. There have been few attempts to use asymptotic non-linear equations without involving age variables, although those were based on very limited data or simple stand structures. Its application in a complex forest system such as a tropical rain forest has not been found. It was part of this study to analyze the potential of this type of equations for individual tree-based modelling for this complex mixed-species stands, then compared with an approach involving linear models, as set out in the next chapter.

CHAPTER 3
METHODS

This chapter deals with three main topics, namely data for modelling, modelling approach, and model evaluation. The section on data for modelling covers kinds of information available for the study, and arrangement and preliminary analysis of the data. The modelling approach section emphasizes various ways of grouping species, functional forms identified and selection of final models. Model evaluation involves statistical and graphical analysis, examination of the models from logical and biological points of view, and criteria for selection of final models.

3.1. DATA FOR MODELLING

3.1.1. Data available for the study

A. PT. ITCI data

Data from 14 permanent growth plots of unlogged and logged-over forest of PT ITCI concession in East Kalimantan, Indonesia, were available for this study. A large number of permanent plots were established between 1970 and 1980 in the concession area (Bremen *et al.* 1990). Fourteen plots were then selected on the basis of data availability for growth and yield study, and were resurrected by TROPENBOS Foundation (Faber, 1992; Eijk-Bos 1995), as part of collaborative research between the Indonesian Forestry Research Agency (Ministry of Forestry) and the TROPENBOS. The total area of the plots was 11.55 ha, with individual plots ranging in size from 0.25 to 2 ha. Their altitude ranged from 100 to 420 metres above sea level. Each plot had been divided into sub-plots of 10 m x 10 m (horizontal distances), resulting in a total of 1025 sub-plots. The plots were measured and re-measured from 1976 to 1982 by PT. ITCI and from 1988 to 1993 by TROPENBOS. Plot locations and characteristics by year of measurement are described in Appendices 3.1 and 3.2; Tables 3.1 and 3.2 respectively.

Tree girth was measured at breast height or above buttresses/irregularities with a girth tape. Measurements carried out by PT. ITCI (1976-1982) and converted to diameter at breast

height or above buttresses/irregularities, were recorded on trees with a minimum of 15 cm; while the ones by TROPENBOS included those with a minimum diameter of 10 cm.

Table 3.1. Characteristics of permanent growth plots of PT. ITCI.

PLOT NUMBER	AREA (ha)	FOREST TYPE	ALTITUDE (m)	SOIL	GEOM. CAT.
71-1v	1.14	virgin dipterocarps	100	poor soil	1
72-8	2.00	virgin dipterocarps	345	poor soil	2
76-3a	0.50	virgin dipterocarps	295	poor soil	3
76-3b	0.75	virgin dipterocarps	285	poor soil	3
76-4	1.65	virgin dipterocarps	260	poor soil	2
76-5	0.25	virgin dipterocarps-Agathis	420	poor soil	2
76-6	0.25	virgin dipterocarps-Agathis	420	poor soil	2
71-1l	0.66	Logged-over dipterocarps	100	poor soil	1
72-1	0.50	Logged-over dipterocarps (1971)	130	better soil	1
72-2	0.50	Logged-over dipterocarps (1971)	130	better soil	1
76-1	1.32	Logged-over dipterocarps (1976)	100	poor soil	1
77-1	0.84	Logged-over dipterocarps (1978)	210	better soil	1
77-2	0.35	Logged-over dipterocarps (1978)	115	better soil	1
77-3	0.84	Logged-over dipterocarps (1978)	210	better soil	1

Source : Bremen *et al.* (1990); Eijk-Bos (1995).
GEOM. CAT (geomorphology):
1 : dominated by asymmetric, non-oriented hills, with local relief between 50 to 300 m, steep slope, and narrow crests and valley floors,
2 : areas of linear ridge systems with steep to very steep dipslopes, local relief between 50 to 300 m, and narrow crests,
3 : mountainous, with steep dissected dipslopes.

Table 3.2. Measurements carried out in permanent growth plots of PT. ITCI.

PLOT NO.	YEAR												
	'76	'77	'78	'79	'80	'81	'82	'83-'87	'88	'89	'90	'91-'92	'93
711-v	*	*	*	*	-	*	*	-	*	-	*	-	*
72-8	*	*	*	*	-	*	*	-	*	-	*	-	*
763-a	*	*	*	*	-	*	*	-	*	-	*	-	*
763-b	*	*	*	*	-	*	*	-	*	-	*	-	*
76-4	*	*	*	*	-	*	*	-	*	-	*	-	*
76-5	*	*	*	*	-	*	*	-	*	-	*	-	*
76-6	*	*	*	*	-	*	*	-	*	-	*	-	*
71-1l	*	*	*	*	-	*	*	-	*	-	*	-	*
72-1	*	*	*	*	-	*	*	-	*	-	*	-	*
72-2	*	*	*	*	-	*	*	-	*	-	*	-	*
76-1	*	*	*	*	-	-	*	-	*	-	*	-	*
77-1	-	-	*	*	-	*	-	-	-	*	*	-	*
77-2	-	-	*	*	-	*	-	-	-	*	*	-	*
77-3	-	-	*	*	-	*	-	-	-	*	*	-	*

Note : * : measurement taken place; - : no measurement
Source : TROPENBOS-Forest Research Institute (BPK) Samarinda (1994); ODA-MOF (1996)

Detailed species identification was carried out only by TROPENBOS between 1988-1990, and so trees which died in earlier measurements could not be identified, thus creating difficulties in grouping species for the purpose of modelling mortality by species groups using data from all measurements periods. Several trees developed buttresses during the gap in re-measurement between 1982 and 1988. Height of diameter measurement for these trees was shifted upwards without measuring the old measurement height, rendering correction of point of measurement to be impossible.

Some difficulties were encountered in deriving data sets from the existing data base for PT. ITCI: for example, irregularity of measurement intervals, variability of measurement frequencies among the growth plots, moving the height at which diameter/girth measurements were made, zero increment and excessive changes (large increment and/or decrement) in diameter between consecutive measurements for a number of tree species. To maximize the use of information available and to try to capture the changes caused by environmental factors, all tree data (with minimum diameter of 15 cm) covering measurements from the 1976 – 1993 period were used. Non-overlapping re-measurement intervals and elapsed times from initial condition (first measurement) were chosen as the basis for calculating diameter increment for linear models and projection time for non-linear models respectively. And to avoid over-prediction of increment in some re-measurement intervals, zero increments were deleted and subsumed within longer times over which calculated diameter increment was greater than zero. Some authors suggested that trees with small decrement should not be omitted since decrement in tropical trees could be as a result of natural variation or bark shading (e.g. Vanclay, 1994b; Alder, 1995). Because of the difficulty in determining whether diameter decrement found in the data set was as a result of measurement error or caused by natural variation or bark shading, trees with diameter decrement between two consecutive measurements were not used as a response variable but were included in calculating stand attributes. Tree diameters in two consecutive measurements, where the height of measurement was raised because of buttresses/ irregularities, were not used for calculating diameter increment nor for predicting future diameter, but they were used to calculate stand attribute/competition measures. This may have induced bias in the growth model predictions, but there is no way of confirming this. On the other hand, excluding these trees from calculating stand attributes would have under-estimated competitive effects, while assuming no changes in diameter between successive measurements would also introduce bias.

The 1993 measurement data were obtained only in the third year of this research. For this reason, the data sets used to fit equations [3.1], [3.2], [3.5], and [3.7] (Equations [1] to [6]

in Chapter 4) cover measurements up to 1990 only; while equations [3.17] to [3.19] (Equations [7] and [8.a-b] in Chapter 4) were fitted to data covering measurements up to and including 1993. In fitting Equations [1] to [6], unidentified trees were used to calculate both diameter increment and stand attributes. For fitting Equations [7] and [8], the unidentified trees were excluded from analysis (used only to calculate stand attributes), after examining residuals (with and without unidentified trees) of the species groups that contained these trees.

B. PT. INHUTANI I data

The PT. INHUTANI I data used in this study consisted of 12 plots each of 4 ha, and each of which had been divided into squares of 1 ha. These plots were established mainly for studying the impact of different logging techniques and intensities on the development of residual stands and their regeneration. The data did not cover as wide ranges of altitude as in the PT. ITCI population (all plots were located at altitudes lower than 100 m above sea level). Furthermore, the data covered only very short periods of measurement (1991-1996), that is 4 times of measurement within 5 years, and logging had taken place before the first re-measurement. Trees with 10 cm minimum diameter at breast height (or above buttresses/ irregularities) were measured with girth tapes. Plot locations and description of each of the 12 plots can be seen in Appendices 3.1 and 3.3, and Table 3.3 respectively.

Table 3.3. Characteristics of permanent plots of PT. INHUTANI I.

PLOT NO.	PLOT CONDITION	NOTES
401	Unlogged	- plot area : 4 ha, each divided into squares of 100 m x 100 m, - interval between measurements: 1 year between first and second measurements, and 2 years thereafter.
402	controlled-logging, cut d > 50 cm	
403	controlled-logging, cut d > 50 cm	
404	Unlogged	
405	controlled-logging, cut d > 60 cm	
406	controlled-logging, cut d > 60 cm	
407	controlled-logging, cut d > 60 cm	
408	conventional-logging, cut d > 60 cm	
409	conventional-logging, cut d > 60 cm	
410	Unlogged	
411	conventional-logging, cut d > 60 cm	
412	controlled-logging, cut d > 50 cm	

Source : Bertault *et al.* (1993), PT. INHUTANI I (1996)

3.1.2. Data arrangement and preliminary analysis for modelling

Several data sets, two sets for PT. ITCI and one set each for PT. INHUTANI I and the combined PT. ITCI/PT. INHUTANI I, were derived from the data bases of PT. ITCI and PT. INHUTANI I data, in a format to enable processing in SAS 6.11/Statistical Analysis System (SAS Institutes, 1995).

A. PT. ITCI data

Two different structures of data sets were created due to : the data coverage available at the beginning of the study period; differences in expressing stand attributes to characterize tree competitive status and model forms examined at different stages of the study. The first data set covering measurement and re-measurement over period from 1976 to 1990 was derived from PT. ITCI data files before the 1993 measurements were made available for this study. Stand attributes (G, $G_{>d}$) were calculated on a plot basis, and, because of the variability of plot size (0.25 – 2 ha), these values were converted to per ha. The reason for using plot level in expressing stand attributes as a measure of competition, was the fact that the structure of tropical rain forests which commonly have trees occupying emergent layers, and in some cases emergent trees far from the subject tree, have more effects in competition than the surrounding trees.

For the purpose of modelling diameter increment (to fit equations [3.1], [3.2], [3.5], and [3.7]), the data were structured as follows:

1. Plt (plot number),
2. TN (tree number),
3. Gn (genus code),
4. Spec (species code),
5. MYR (year of measurement carried out in a plot),
6. d (tree diameter at breast height or above buttresses/irregularities outside bark in cm),
7. d_i (diameter increment in cm/year),
8. SQ (soil quality characteristics),
9. alt (altitude in m above sea level),
10. geom (geomorphology),
11. lov (whether or not a plot had been logged),
12. G (basal area, calculated on a plot basis in m^2/ha),
13. $G_{>d}$ (overtopping basal area, calculated on a plot basis in m^2/ha),
14. Grp4 (species group codes into 4 groups of L, M, S, U),
15. Grp8 (species group codes into 8 groups of LF, LS, MF, MS, SF, SS, UF, US),
16. $P\{Int[d_1+(d_2-d_1)/(t_2-t_1)]> Int[d_1]\}$

Explanations of how the above sixteen variables were obtained are outlined below. Variables no. 1 to 5 were extracted from the PT. ITCI data files. Tree girth records in mm

were converted to diameter (variable no. 6) in cm (d=girth/10π), and tree diameter increments (variable no. 7) were calculated ($d_i = (d_2-d_1)/(t_2-t_1)$). Height of girth measurements was not included in this data set; the value of d_i was set to a missing value when height of girth measurement was shifted upwards because of buttresses. Variables no. 8 to 16 were derived in SAS from variables 1 to 7 and information in Table 3.1. SQ and lov were dummy variables which take the value 1 for better soil and 0 for poor soil, lov=1 for logged plots and 0 for virgin/unlogged plots respectively. The classification of soil quality characteristics into poor and better soil was based on Bremen *et al.* (1990); that is, better soil refers to a more favourable nutrient status in the A Horizon. Geomorphology takes the value 1, 2, or 3 (see Table 3.1). Variables G and $G_{>d}$ were calculated on a plot basis and converted to per ha values. Because of the large variation in plot size (0.25 to 2 ha) the same $G_{>d}$ might have had a different effect on the response variable if the value of $G_{>d}$ were determined as plot basal area greater than the subject tree without such conversion. For this reason, the value of d for $G_{>d}$ was determined arbitrarily at a cut-off point at $G_{>d}$=30 cm. The variables d_i, P, and $d_i/(d_{max}-d)$ were the response variables used for fitting linear, probabilistic linear, and modified beta functions respectively in Equations [1] to [6] (equations [3.1], [3.2], [3.5], and [3.7] of this chapter). The variable $G_{>d}/\ln(d+1)$, introduced by Wykoff (1990) as a competition factor, was also used in this study. Wykoff (1990) found that interaction between tree size and basal area of larger trees ($G_{>d}/\ln(d+1)$) resulted in better predictions than $G_{>d}$ alone.

The second data set was created after the 1993 measurement data became available. In order to maximize the use of all information available and to try to capture the changes caused by environmental factors, a data set covering all measurements within the 1976 to 1993 period was then derived. Since the data contained large numbers of zero increments (about 15 %), these zero increments were excluded from the analysis and subsumed within longer times over which calculated diameter increment was not zero, in order to avoid over-prediction of increment in some re-measurement intervals. No individual records, however, were deleted from the data derived. Stand attributes G and $G_{>d}$ were expressed on a sub-plot (0.01 ha) basis, but were not extrapolated to per ha values because of a great variation in sub-plot basal area. The variable $G_{>d}$ was calculated as accumulated basal area (in a sub-plot) greater than the subject tree. Other measures of competition such as : a measure of tree dominance (tci) introduced by Alder (1995), and basal area excluding the subject tree ($ci = G_{sp}-g$) in a sub-plot, were also examined. The variable tci was obtained from $1-(G_{>d}/G_{sp})$, and

so the most dominant tree in a sub-plot would have the tci value of 1 and the least dominant one would take the tci value close to 0.

The following is the structure of the data set derived from the PT. ITCI data files covering measurements up to and including 1993, used to fit both equation to predict future diameter (non-linear model) and diameter increment (linear model):

1. Plt (plot number),
2. Subp (sub-plot number),
3. TN (tree number),
4. Gn (genus code),
5. Spec (species code),
6. MYR1 (date/month/year of measurement at t_1),
7. MYR2 (date/month/year of measurement at t_2),
8. MH1 (height of measurement at t_1),
9. MH2 (height of measurement at t_2),
10. d_1 (tree diameter in cm at t_1),
11. d_2 (tree diameter in cm at t_2),
12. dt (interval between measurements = myr_2-myr_1),
13. g_1 (tree basal area in m^2 at t_1),
14. g_2 (tree basal area in m^2 at t_2),
15. G_{sp} (sub-plot basal area in m^2/0.01ha),
16. $G_{sp>d}$ (sub-plot basal area of trees with diameter greater than the subject tree in m^2/0.01ha),
17. ci (sub-plot basal area excluding the subject tree in m^2/0.01ha),
18. tci (a measure of tree dominance = $1-(G_{sp>d}/G_{sp})$),
19. alt (altitude in m above sea level),
20. lov (whether or not a plot has been logged),
21. SQ (soil quality characteristics),
22. geom (geomorphology),
23. Grp4 (species group codes for 4 species groups of LUF, LMUS, MeSF, SmaS),
24. Grp8 (species group codes for 8 species group).

B. PT. INHUTANI I data

A data set derived from PT. INHUTANI I data files had similar structure to the second data set derived from the PT. ITCI data files.

1. Plt (plot number; refer to 1 ha square in PT. INHUTANI I data files),
2. Subp (sub-plot number),
3. TN (tree number),
4. Gn (genus code),
5. Spec (species code),
6. X (axis 1 for tree coordinate)
7. Y (axis 2 for tree coordinate)
8. MYR1 (date/month/year of measurement at t_1),
9. MYR2 (date/month/year of measurement at t_2),

10. d_1 (tree diameter at breast height or above buttresses/irregularities outside bark in cm at t_1),
11. d_2 (tree diameter at breast height or above buttresses/irregularities outside bark in cm at t_2),
12. dt (interval between measurements = MYR_2-MYR_1)
13. g_1 (tree basal area in m^2 at t_1),
14. g_2 (tree basal area in m^2 at t_2),
15. G_{sp} (sub-plot basal area in m^2/0.01ha),
16. $G_{sp>d}$ (sub-plot basal area of trees with diameter greater than the subject tree in m^2/0.01ha),
17. ci (sub-plot basal area excluding the subject tree in m^2/0.01ha),
18. tci (a measure of tree dominance = $1-(G_{sp>d}/G_{sp})$)
19. lov (whether or not a plot had been logged),
20. SC (soil category),
21. GC1 (girth code at MYR1; refers to height of measurement),
22. GC2 (girth code at MYR2; refers to height of measurement),
23. Ldf1 (tree damage codes caused by logging at MYR1),
24. Ldf2 (tree damage codes caused by logging at MYR2),
25. Lds1 (tree damage codes caused by skidding at MYR1),
26. Lds2 (tree damage codes caused by skidding at MYR2),
27. Grp5 (species group codes for 5 groups),
28. Grp8 (species group codes for 8 groups).

Explanations of the above data structure are as follows. A plot number (variable Plt) was given to each 1 ha square, and so, a total of 48 plots were able to be derived from the 12 original plots of PT. INHUTANI I data files. Sub-plot information was not available from the PT. INHUTANI I data files. This variable was derived using tree coordinate information (variables X and Y), so that stand attributes (G_{sp}, $G_{sp>d}$, ci, and tci) could be calculated on a sub-plot basis. Species was recorded by full scientific name, and so codes for genus and species (variables Gn and Spec) had to be created and adjusted to conform with the species coding for the PT. ITCI data. The species codes were created using a Visual dBase programme. Variables d_1 and d_2 were converted from tree girth records, and only trees with minimum diameter at breast height or above buttresses/irregularities of 15 cm and above (>14.495 cm) were considered. Soil category (SC) was a dummy variable which takes the value 1 for plots of 1 ha (see Appendix 3.3) located in soil category Uc3 (Udults soil group, clay-stone soil parent material, with well drained condition); and 0 for plots located in other soil categories. This variable was derived using results of a soil study conducted by Sumaryono (1996). A plot with at least 75 % containing Uc3 soil category was included in SC=1 (15 plots). Among the other 33 plots which were included in SC=0; 27 plots of them were mixtures of several soil categories, and 6 plots each of : 1, 2, and 3 plots, belonging to the following 3 different soil categories : Us3 (Udults soil group, sandy-stone parent material, with well drained condition), Fsi4 (Fragiudults soil group, silt-stone parent material, with very

well drained condition), and Uc2 (Udults soil group, clay-stone parent material, with imperfectly drained).

C. Combined PT. ITCI/PT. INHUTANI I data

A combined data set, extracted from the data structured in earlier sections (A and B) was derived. For logged plots of PT. INHUTANI I data, only trees without damage caused by logging or skidding were used in the analysis. All living trees greater than 15 cm in diameter at breast height or above buttresses/irregularities outside bark, however, were used for calculating stand attributes. The following is the structure of the combined data :

1. Dat (ITC : data from PT. ITCI; INH : for data from PT. INHUTANI I),
2. Plt (plot number),
3. Subp (sub-plot number),
4. TN (tree number),
5. Gn (genus code),
6. Spec (species code),
7. MYR1 (date/month/year of measurement at t_1),
8. MYR2 (date/month/year of measurement at t_2),
9. d_1 (tree diameter at breast height or above buttresses/irregularities outside bark in cm at t_1),
10. d_2 (tree diameter at breast height or above buttresses/irregularities outside bark in cm at t_2),
11. dt (interval between measurements = MYR_2-MYR_1)
12. g_1 (tree basal area in m^2 at t_1),
13. g_2 (tree basal area in m^2 at t_2),
14. G_{sp} (sub-plot basal area in m^2/0.01ha),
15. $G_{sp>d}$ (sub-plot basal area of trees with diameter greater than the subject tree in m^2/0.01ha),
16. ci (sub-plot basal area excluding the subject tree in m^2/0.01ha),
17. tci (a measure of tree dominance = $1-(G_{sp>d}/G_{sp})$),
18. lov (whether or not a plot had been logged),
19. loc (locality; loc=1 for PT. ITCI data, loc=0 for PT. INHUTANI I data).

After a data set was derived, preliminary data analysis was done by plotting possible response variables (in this case d_2 and d_i) against all possible explanatory variables to check the distribution of the data. An observation or a group of observations too far removed from these remaining observations (outliers or influential observations) were subject to re-checking. Some other procedures in SAS such as PROC MEANS, PROC UNIVARIATE were also used in analyzing the reliability of the data.

3.2. MODELLING APPROACH

Individual tree-based distance-independent modelling was used to model diameter growth of selected areas of the PT. ITCI and PT. INHUTANI I forests in East Kalimantan. Selection cutting is the silvicultural system used in Indonesia's tropical rain forests, and guidelines from the Ministry of Forestry determine the minimum diameter at breast height or above buttresses/irregularities of trees and tree species that are allowed to be cut. For this purpose, individual tree based models, which maintain species identity and which utilize diameter growth as the response variable have practical advantages. Furthermore, in the case of increment model, although some authors argued that basal area increment model has theoretical advantages because the correlation between basal area increment and initial diameter is greater than the one between diameter increment and initial diameter, there has not been conclusive evidence that basal area increment model is superior to diameter increment model (see West, 1979; Wan Razali, 1988).

Due to limitations in the data, which have been explained in section 3.1, modelling was started using the PT. ITCI data, because, as has been stated previously, these data covered longer measurement period, provided more detailed species identification, and had a wider range of locality factors such as altitude, than did the PT. INHUTANI I data. Furthermore, the PT. INHUTANI I data had not been able to be obtained until the third year of this study. For these reasons, only the PT. ITCI data was used to examine various functional forms described in section 3.2.2.

Separate models were developed for each as well as for the two localities combined. Only the Gompertz projection form was used to model diameter growth of the PT. INHUTANI I data and the combined PT. ITCI/PT. INHUTANI I data, based on the results previously obtained from modelling the PT. ITCI data alone.

3.2.1. Species grouping

A typical feature of tropical rain forests which can be readily found is that there are large numbers of species but many of them are represented by only a few trees. Their growth rates vary greatly, and so it is unlikely that one model can be developed for all species. Conversely it is not possible, at least at this stage, to develop one model for each species. Species need to be grouped using criteria which appropriately reflect the intended use of the model being built, and also take cognisance of the data available for building the model.

PT. ITCI data were used first to examine various ways for species grouping. The first attempt in identifying ways of aggregating species was to examine whether the "importance value index (IVI)" of a species by Curtis (1959) based on the IVI calculation done by TROPENBOS (Eijk-boss, 1995), that is the sum of relative density, relative frequency, and relative dominance, could be used as a criterion for species grouping. Results from checking these values and the corresponding diameter increment suggested that the IVI did not seem to be a good way for species grouping for the purpose of modelling in this research, as many species with the same IVI had a great variation in growth rate.

The species were then ranked, based on the number of observations (number of measurements). Genera from species with large numbers of observations were assigned as separate groups and then other species from the same genus were added to the same groups. A similar problem to the IVI one was encountered, in that species from the same genus varied greatly in growth rate.

Grouping species based on mean diameter growth rate was also investigated. Plotting data (tree diameter increment against initial diameter) was done before calculating mean diameter increment for individual species, for checking possible errors in the data. Species were ranked in order of decreasing numbers of observations. Species with the highest number of observations was assigned as founding species of group 1. The mean observed diameter increment of the first 20 species from higher ranks were compared using Tukey's studentized range (HSD) test, and species which did not show significance differences in mean diameter increment at $\alpha = 0.05$ were aggregated into the same groups. The species groups formed from the first comparison were then compared with incoming species (20 species/species groups in each comparison) until all species were assigned into groups. It resulted in 43 species groups, but the procedure was tedious and there was no guarantee that the grouping would be satisfactory. Since the data consisted of many species with very limited number of observations, analysis of their growth pattern statistically is restricted. Moreover, the data cover only the period of measurements between 1 to a maximum of 15 years, which may not indicate growth patterns reliably, especially for this particular forest where many species have high longevity.

Because of limitations of the data for this study in terms of the representation of each species, and after exploring possible ways for species grouping, species were aggregated using ecological criteria such as maximum attainable size (potential to occupy certain canopy layers) using published and observed data, and local knowledge. Information regarding

maximum attainable size (height and diameter a species could possibly attain or in some cases height or diameter only) for many species of this forest were available (for example in Whitmore 1972, 1973; Ng, 1973, 1989; and Sidiyasa *et al.* 1990). Most of species for which information on the maximum attainable size were not available had been identified only up to family or genus level, or occurred with only little representation.

Using criteria of maximum attainable size, species were aggregated into four groups, namely: large, medium, small tree species, and one other group to accommodate species in which maximum attainable size were unknown. The species groups were then broken down into faster and slower growing species using average observed diameter increment per 1 cm diameter class. Species with average diameter increment ≥ 0.5 cm per year was grouped as faster growing species, whereas those with diameter increment < 0.5 cm per year were included as slower growing species groups; this resulted in eight species groups of : large faster growing species (LF), large slower growing species (LS), medium faster growing species (MF), medium slower growing species (MS), small faster growing species (SF), small slower growing species (SS), other faster growing species (UF), and other slower growing species (US). Diameter increment greater or less than 0.5 cm per year was determined as the basis for separating between faster and slower growing species, after observing the distribution of diameter increment, in trying to reduce the accumulation of the data in slower growing groups.

The species grouping was further examined during the process of modelling. Various functional forms were fitted to data with the various ways of species grouping. Accordingly, the appropriateness of species grouping and model quality could be examined jointly. It was also found useful to identify which variables were likely to be important in affecting diameter growth of this particular forest, and which variables were likely to be group or functional form dependent. The following functional forms were fitted to different species groups :

Step 1.

Linear multiple regressions (Equations [3.1] and [3.2]) and modified beta functions (Equation [3.5]) were applied to 8 species groups of LF, LS, MF, MS, SF, SS, UF, US. Based on the results of fitting these two kinds of equations to the 8 species groups, then re-grouping the various species and re-defining explanatory variables to be included in the models, were then considered. Four groups of large, medium, small, and other tree species, were finally selected to be examined.

Step 2.

Linear (Equation [3.2]) and modified beta functions (Equation [3.5] were applied to 4 species groups of large, medium, small, and other tree species (L, M, S, U); as well as to all species together. A probabilistic function (Equation [3.7]) was also examined with the 4 species groups data. From analysis of the first and second steps, other functional forms were explored, species grouping was re-examined, and variables included in the equations were re-defined.

Step 3.

Three sigmoid growth equations (Equations [3.11] to [3.13]) were fitted to several individual species with many data, using only 1 year interval data. Based on these results, step 4 was undertaken in order to examine the possibility for grouping species based on similarity in model fit.

Step 4.

A Gompertz projection form with sub-plot basal area (G_{sp}) as an additional term and tree basal area at time 2 (g_2) as the response variable, was fitted to individual species with a minimum number of observations of 30 (80 species among 491 species), using mixed interval lengths. The estimates of parameter α for many species were unrealistic (Appendix 3.4), and so they were discarded from further analysis. This lack of success might have been associated with problems in fitting non-linear models to too few data (Ratkowsky, 1990). Based on this result, some other forms were investigated.

Step 5.

A Gompertz growth (Equation [3.12]) and its linearized form (Equation [3.14]) and an ED-analogue (Equation [3.15]) were fitted to 4 species groups, comprising large and other faster growing species (LUF); large, medium, and other slower growing species (LMUS); medium and small faster growing species (MeSF); and small slower growing species (SmaS). The 4 groups represented a further aggregation of the 8 species groups, based on results of Tukey's studentized range (HSD) test. The average observed diameter increments (d_i) per 1 cm diameter classes for the 8 groups were compared one with another, and then the groups with mean d_i not-significantly different (α=0.05) were amalgamated. The Gompertz growth form (Equation [3.12], incorporating stand attributes and locality factors, was fitted to the data with short ($\leq$ 2 years) and mixed intervals, while the ED-analogue (Equation [3.15]) was fitted to mixed interval data only. Both equations resulted in clear bias of residuals, and so, they were discarded from further examination.

Step 6.

A Gompertz projection form (Equation [3.17]) was next fitted to 8 species groups, and all species together, with each group accorded a dummy variable. Based on these results, the equation was then fitted to the four species groups of LUF, LMUS, MeSF, and SmaS.

Step 7.

The Equation [3.17] was fitted to 4 species groups of LUF, LMUS, MeSF, and SmaS. Through various ways of examination, these 4 species groups were selected as the final species groups formed in this study to characterise diameter growth for the PT. ITCI data.

The equations in steps 1 and 2 were fitted to data from 1976-1990 measurements, and stand attributes were calculated on a plot basis then converted to per ha values; while the latter equations (in steps 3 to 7) were fitted to data covering measurements up to 1993, and stand attributes were calculated on a sub-plot basis.

The same criteria for grouping species of PT. ITCI data (maximum attainable size and average observed diameter increment per 1 cm diameter class) were used to aggregate 640 species codes of PT. INHUTANI I. Eight groups of large, medium, small, and other tree species, each broken down further into faster and slower growing species, were initially formed. Only 46 % of the 640 species codes covered tree identifications up to species name level of detail; the rest of the species codes were up to only genus or family level. As a result, most species fell into groups comprising other faster or slower growing species. The possibility for further species aggregation into smaller groups was also examined.

Combined PT. ITCI and PT. INHUTANI I data comprised 1013 species: some 110 species existed in both localities. Clear differences in level of detail in species identification between the PT. ITCI and PT. INHUTANI I data, caused difficulty in grouping species when both data sets were combined. Many species in PT. INHUTANI I data were identified up to family or genus level only, and so, it was possible that trees which in PT. INHUTANI I data were under the same family or genus name, fell into different species names in PT. ITCI data. Accumulation of the data in the category 'other tree species' was unavoidable, therefore, considering these difficulties. The following three different ways of aggregating species were examined for the combined data, in order to identify which sets of grouping provided the best fit for the data.

1. Aggregation of species into 10 species groups of large faster growing species (LF), large slower growing species (LS), medium faster growing species (MF), medium slower

growing species (MS), small faster growing species (SF), small slower growing species (SS), faster growing dipterocarps (DF), slower growing dipterocarps (DS), faster growing non-dipterocarps (NF), and slower growing non-dipterocarps (NS). The first 6 groups were formed from species which existed in both localities, while species which were found only in one of the two localities fell into the last 4 groups;

2. Aggregation of species into 8 groups of LF, LS, MF, MS, SF, SS, UF, and US. In this way, the species group DF from the first grouping, fell into groups LF, MF, and UF, the DS into groups LS, MS, and US, while the NF and NS fell into large, medium, small and other faster growing species, and slower growing species respectively;

3. Grouping species into 4 groups of DF, DS, NF, and NS.

Other slower growing species accounted for the biggest proportion in both PT. ITCI and PT. INHUTANI I data. Aggregating species pertaining to the combined data into 4 and 10 species groups (the first and third ways of grouping) resulted in 60 % and 45 % of the total number of observations respectively falling into Group NS. Species aggregation into 8 groups (the second way of grouping), yielded the least concentration of data in one group among the earlier two ways of grouping (34 % for Group US).

Lists of species codes and names for each group for PT. ITCI and PT. INHUTANI I data can be seen in Appendices 3.5 and 3.6. Summary of PT. ITCI, PT. INHUTANI I, and the combined PT. ITCI/PT. INHUTANI I data for each species group are presented in Appendices 3.7, 3.8, and 3.9 to 3.11 respectively.

3.2.2. Growth modelling

One of the objectives for this research was to identify the most suitable model to characterize diameter growth of the particular forest under study, using the approach stated earlier in this chapter. Modelling began using linear functions (in this case multiple linear regression models), which are the most widely used functional form for individual tree based modelling of temperate and tropical rain forests, for even-aged single species plantations and for indeterminate-aged mixed species. A modified beta function used by Vanclay (1989), then by Alder (1995), was also investigated in this study. Some researchers have demonstrated the potential of probabilistic functions to be used in individual tree based modelling, particularly for modelling mortality (for example: Buckman, 1979; Hamilton,

1974, 1986, 1990; Monserud, 1976; Ong and Kleine, 1996; Vanclay, 1991c; Wan Razali, 1989), and recruitment and or regeneration (Vanclay, 1992). Vanclay (1991d) used this function for modelling diameter growth of North Queensland rain forest. This function was also examined in this study. A very popular functional form (sigmoid functions) used in stand level modelling in even-aged plantation forest, but rarely used for ageless stand modelling was also studied.

A. PT. ITCI data

Three different SAS procedures were used to fit the functions to data, namely PROC REG (regression procedure), PROC LOGISTIC (logistic procedure), and PROC NLIN (non-linear procedure); they were applied to the linear and modified beta functions, probabilistic function, and sigmoid functions respectively.

Linear function

The term linear function used here refers to a standard least-squares multiple regression model. This model has been widely used in forestry and other disciplines. The two following functional forms, commonly found in forestry applications, were firstly examined :

[3.1] $\ln d_i = \beta_0 + \beta_1 d + \beta_2 d^2 + \beta_i$ (stand attributes) $+ \beta_j$ (locality factors)
(Equation [1] in Chapter 4), originated from $d_i = \beta_0 + \beta_1 d + \beta_2 d^2$; where $\beta_1 > 0$ and $\beta_2 < 0$ (see Alder, 1995 p. 114)

[3.2] $\ln d_i = \beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i$ (stand attributes) $+ \beta_j$ (locality factors)
(Equations [2] and [4] in Chapter 4), originated from $\ln d_i = \beta_0 + \beta_1 \ln d + \beta_2 d^k$; where $k = 1$ (see Vanclay, 1994 p. 166).

The equations [3.1] and [3.2] were fitted to 8 species groups (see step 1 section 3.2.1), using PROC REG (regression procedure in SAS). The later equation (Equation [3.2]) was also fitted to 4 species groups (see step 2 section 3.2.1). This procedure fits linear regression models by the least-squares method. Stepwise regression was chosen to select subsets of explanatory variables which best improve predictions of the response variable. A default criterion for a variable entering (SLE) or staying (SLS) in the model (SLE=0.15; SLS=0.15), was initially used to examine the importance of each explanatory variable under investigation to the

response variable. The procedure starts with no variable in the model, then adds variables one by one, while the F statistic for a variable added is significant at the level set for staying in the model (SLS=0.15). Variables in the model which are not significant at the level set for staying in the model, are then deleted. The procedure ends when no variable outside the model is significant at SLE=0.15, and every variable in the model is significant at SLS=0.15, or when the variable added to the model is just deleted. However, significant level of at least 0.05, unless otherwise, was used to select explanatory variables to be included in the models.

Based on the concept that d_i = f (initial size and other factors), the first attempt involved checking the effect of variables d, d^2 (Equation [3.1]) and d, ln d (Equation [3.2]) on predicting the response variable d_i. The procedural steps were continued by forcing the first two variables (d, d^2 or d, ln d) to stay in the model. The sign and magnitude of the coefficients were checked. Non-significant variables, or variables with anomalous signs of the coefficients were not automatically discarded, because this problem might be associated with autocorrelation, and multicollinearity. The equations with various combinations of explanatory variables were fitted to data. Their residual pattern and distribution, as well as summary statistics and graphical plots from the SAS univariate procedure (see section 3.3.1) were compared. The sign of the coefficient for each variable was checked. In addition, other criteria like the Durbin-Watson (DW) statistic, the value of the largest condition index and variance inflation factors (see section 3.3.1), as well as the growth trend in terms of its biological realism, were also used in examining the appropriateness of a model.

Modified beta function

Vanclay (1989a) proposed the following equation for predicting tree diameter increment :

[3.3] $di = f(G, SQ, PM)\ (d_{max}-d)\ d^k$

where G is plot basal area expressed per ha, SQ is soil quality, and PM is parent material.

Alder (1995) linearized this function by taking the logarithm of both sides, and modifying it to :

[3.4] $\ln(d_i/(d_{max}-d) = a + b \ln(d)$

The Equation [3.4], was further modified to include stand attributes and locality factors :

[3.5] Ln $(d_i/(d_{max}-d))$ = f (stand attributes, locality factors) + b ln d
(Equations [3] and [5] in Chapter 4)

The same procedure as for Equations [3.1] and [3.2] was used to fit the function to species groups in steps 1 and 2 section 3.2.1. Stand attributes and locality factors used were the same as the ones for the linear functions.

A possible limitation of the function is the problem of determining the value of d_{max}. Only a few large trees were available in the data set, and so this lack virtually precludes the use of statistical analysis to determine d_{max}. Vanclay (1989a) addressed this problem and suggested determination of d_{max} subjectively for each growth group and soil parent material based on available data, and local knowledge. In this study, the three following different values of d_{max} were determined subjectively and results were then examined: observed d_{max} of the group, d_{max} of the largest species in a group based on published data, and an arbitrary value of d_{max} after checking the value of observed d_{max} for the group. The later two d_{max}'s resulted in very high max d_i, that is unrealistic for the species under study. These results were also discarded from further analysis. Results presented in Chapter 4, used observed d_{max} of the groups.

Probabilistic function

The basic form of the function can be expressed as :

[3.6] $p = e/(1+e)$

The following function was fitted to 4 species groups of PT. ITCI data (see step 2 section 3.2.1), using PROC LOGISTC (logistic procedure) in SAS 6.11.

[3.7] $p = (1+\exp[\beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i (G, G_{>d}, \ln G, \ln G_{>d}) + \beta_j (SQ, alt, geom)])^{-1}$
(Equation [6] in Chapter 4)

The logistic procedure fitted the linear logistic model using maximum likelihood estimators. Stepwise regression was the method used for model selection.

Despite the advantages noted by Vanclay (1994a), that the probabilistic function is robust in the presence of outliers, and simplifies the construction of compatible deterministic/stochastic growth models, it caused difficulties, however, when compared with other functional forms examined in this study using general fitting criteria.

Sigmoid function

Sigmoid functions (asymptotic non-linear equations) in either projection or growth form have been widely used for stand level modelling in plantation forests, where stand ages are known and which in most cases refer to a single species. Use of such equations in modelling growth of mixed-species is limited by the fact that age is an important driving variable but it is not always available in mixed-species growth data.

This study examined the three following sigmoid functions which have been widely used for studying plant growth in agricultural crops as well as in forestry (see Causton and Venus, 1981; Hunt, 1982; and Zeide, 1993). In integral (yield) form, the functions are expressed as follows :

[3.8] $Y = \alpha\,[1 - \exp(-\beta t)]^{\gamma}$ (Chapman-Richards)

[3.9] $Y = \alpha \exp[-\beta \exp(-\gamma t)]$ (Gompertz)

[3.10] $Y = \alpha/[1 + \beta \exp(-\gamma t)]$ (Logistic)

where Y is size at time t; α is the asymptote; β and γ are parameters specific to the equations.

Also, the following are the corresponding differential (growth) forms (see Woollons, 1989; and Zeide, 1989).

[3.11] $dy/dt = \alpha\, y^{\gamma} - \beta\, y$ (Chapman-Richards)

[3.12] $dy/dt = \alpha\, y - \beta\, y \ln y$ (Gompertz)

[3.13] $dy/dt = \alpha\, y - \beta\, y^2$ (Logistic)

where dy/dt is the change in size within the period of dt; y and ln y are initial size and its logarithm; α, β, and γ are parameters to be estimated.

Reasons for investigating these functions in this study were related to the properties the functions possess; firstly, these functions do not involve the variable age when expressed in growth forms, and are thus suitable for the data used in this study; secondly, these functions allow the use of elapsed time from first condition rather than age when expressed in projection forms, and so enable one to use interval between measurements to express t2-t1 (see Equation [3.16]).

Zeide (1993) defined the above equations as TD or YD forms (growth declines proportional to age or size).

[3.14] $\ln (dy/dt) = k + p \ln. y + q y = k_1 y^p e^{qy}$

where $p > 0$, $q < 0$, and $k_1 = e^k$. The value of parameter p is equal to 1 for the Gompertz equation, <1 for the Chapman-Richards, and 2 for the Logistic.

Shvets and Zeide (1996) proposed the following ED-analog:

[3.15] $dy/dt = a_1 y^p - a_2 y$

where a_1, a_2, and p are parameters to be estimated, and y is initial size.

The growth form of the Chapman-Richards, Gompertz, and logistic functions (Equations 3.11 to 3.13) were initially fitted to 1 year measurement interval data from several individual species which represented the largest number of observations in the PT. ITCI data, using PROC NLIN (non-linear procedure) with secant method (DUD) in SAS; while Equations 3.14 and 3.15 were fitted to four species groups of LUF, LMUS, MeSF, and SmaS, using short and long intervals, using PROC REG and PROC NLIN respectively. Response variable dy/dt referred to tree diameter increment (cm/year), and y was the diameter (cm) at the beginning of each measurement year.

Based on the initial results of fitting Equations [3.11] to [3.15] to several individual species and species groups (see steps 3 to 5), the Gompertz function was chosen for modelling and re-examining ways of species grouping for the forest under study. Since the data consisted of longer measurement intervals (up to 8 years), the projection form (Equation [3.16]) is probably more suitable than one of growth form (see step 6 in section 3.2.1).

[3.16] $y_2=\text{Exp}(\text{Ln}(y_1).\text{Exp}(-\beta(t_2-t_1)+ \alpha (1-\text{Exp}(-\beta(t_2-t_1))))$

where y_1 and y_2 are size at time 1 and 2, t_2-t_1 refers to number of years between measurements, α and β are parameters to be estimated. The response variable y_2 was replaced by d_2 (tree diameter at time 2 in cm), and y_1 by initial diameter (tree diameter at time 1 in cm), obtained the following equation (Equation [3.17]).

[3.17] $d_2=\text{Exp}(\text{Ln}(d_1).\text{Exp}(-\beta(t_2-t_1)+\alpha(1-\text{Exp}(-\beta(t_2-t_1))))$ (Equation [7] in Chapter 4)

Equation [3.17] was further modified to include stand attributes and locality factors, then fitted to several sets of species groups of the PT. ITCI. Stand attributes used included: sub-plot basal area (G_{sp}) in m^2/0.01 ha, sub-plot basal area excluding the subject tree (ci) in m^2/0.01 ha, sub-plot basal area of trees with diameters greater than the subject tree ($G_{sp>d}$) in m^2/0.01 ha, an index of tree dominance (tci), that is 1-($G_{sp>d}$)/G_{sp}, with a value between 0 to 1 (the more dominant trees, the bigger tci value). Altitude of plots (alt) in m above sea level and plot condition (lov : logged or virgin/unlogged) were the locality factors firstly included in the model, where lov=1 for logged plots and 0 for unlogged/virgin plots . Interactions between variables like alt and lov, ci and tci, tci and $G_{sp>d}$ were also investigated. Soil quality characteristics, expressed as poor (SQ=0) and better soil (SQ=1); and geomorphology (geom) were also examined for the final four species groups.

The Chapman-Richards projection form was also fitted to the four species groups, but found to be very difficult to converge. A similar problem was also stated by Seber and Wild (1989), that convergence difficulty and serious ill-conditioning have often been experienced when fitting this function to data. Ratkowsky (1990) also pointed out this same deficiency of the Chapman-Richards function, despite its being widely used in forestry research; he stated that 'its worst behaving parameter is α, especially when there are few data points near asymptotes'.

Comparison between linear and non-linear equations

Problems in fitting non-linear models to growth data have been addressed in several previous research publications, but detailed discussion in comparing both types of models was not found. Furthermore, the finding in this study suggested the potential of the Gompertz projection form (non-linear model) for aged-indeterminate individual tree based modelling. Considering this finding on the one hand, and the popularity of linear model on the other; attempts in this study were made to compare the performance of both model types. The

following linear models were selected to be compared with the chosen Gompertz projection form.

[3.18] $\sqrt{d_i} = \beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i$ (stand attributes) + β_j (locality factors)
(Equation [8.a] in Chapter 4)

[3.19] $\sqrt{d_i} = \beta_0 + \beta_1 d + \beta_2 d^2 + \beta_i$ (stand attributes) + β_j (locality factors)
(Equation [8.b] in Chapter 4)

These equations were fitted using the same procedures as for Equations [3.1] and [3.2].

Because the non-linear model used d_2 as a response variable, while the linear one used $\sqrt{d_i}$ both equations had to be compared in the same form of response variable. Since there is no formal procedure which can satisfy this comparison in every sense, the following ways of comparing were taken. All calculations were done using SAS programme (SAS 6.11) and graphs were created in Microsoft Excel '97.

Comparison between linear and non-linear models in projection form (d_2)

1. Mean residual d_2 values over ranges of actual intervals for each species group were calculated, and graph of mean residuals against measurement intervals were produced and analysed. The following procedure was adopted for the calculation of mean residuals for each model form:

   $$\textit{Mean residuals}_{\textit{(for each interval length)}} = \Sigma (d_{2\,actual} - d_{2\,predicted}) / \textit{number of observations}$$

   to obtaion $d_{2\,predicted}$: for the non-linear model, the fitted d_2 was used, while for the linear model, $\sqrt{d_{i\,predicted}}$ was transformed back to d_i (predicted), and $d_{2\,predicted}$ were calculated as:

   $$d_{2\,predicted} = d_1 + \Sigma\, d_{i\,predicted}, \text{ where } \Sigma d_{ipredicted} = d_{ipredicted} * \text{interval length}$$

2. Graphical plots of residuals $d_{2\,observed}$ against $d_{2\,predicted}$, and Proc univariate output (residuals d_2) from linear model, were compared with the ones for the non-linear.

Comparison between the linear and non-linear models in increment form (d_i)

1. Residuals for all intervals were calculated, then plots of residuals d_i against average predicted d_i were produced and analyzed. The following procedures for calculation of residuals for each model form were used:

For the linear model, $\sqrt{d_{i\ predicted}}$ was transformed back to $d_{i\ predicted}$, and for the non-linear model, $d_{2\ predicted}$ was used to calculate $d_{i\ predicted}$,

$d_{i\ predicted} = (d_{2\ predicted} - d_1)/interval\ length.$

2. Mean residuals of $d_{i\ predicted}$ over two (short and long) different ranges of observed interval were calculated, and graphs of mean residuals against observed diameter classes for both interval length were produced and analysed. The mean residuals of $d_{i\ predicted}$ were calculated as follows :

$Mean\ residuals_{(for\ short\ or\ long\ interval)} = (d_{iactual} - d_{ipredicted})/number\ of\ observations;$

to obtain $d_{ipredicted}$ for both linear and non-linear models, see no. 1 above.

3. Graphs of growth trends (d_i in cm/year) were produced for each species groups from the fitted models of both model types. The values of diameter increment (d_i) for both model types were obtained by the following procedure:

For the non-linear model, the value of d_i was obtained from the selected equations, using t_2-t_1=1 year, so that $d_i = d_{2predicted} - d_{1(initial\ diameter)}$, and for the linear model, the value of d_i was obtained by back transformation of $\sqrt{d_{i\ predicted}}$ to d_i.

B. PT. INHUTANI I and the combined PT. ITCI/PT. INHUTANI I data

As explained in an earlier section, only the Gompertz projection form was fitted to PT. INHUTANI I and the combined PT. ITCI/PT. INHUTANI I data. Analysis was mainly on how the model which was found to be the best for characterising diameter growth of the PT. ITCI data among various functional forms tested, behaved when both PT. ITCI and PT. INHUTANI I data were modelled separately, and when both data sets were combined. Examination for further aggregation of PT. INHUTANI I species data was carried out, and three different ways of species grouping for the combined data as stated earlier in this chapter were analysed. The best models which could be obtained from this endeavour, were selected using the same criteria as for the PT. ITCI data.

3.3. MODEL EVALUATION

There is quite a bit of jargon used in model evaluation; most researchers use the terms *model calibration* and *validation*, which, in forest growth modelling, involves qualitative and quantitative tests of the model. (Vanclay and Skovsgaard, 1996) used terms *model criticism* and *benchmarking* for different steps of model evaluation. Despite the differences in terms being used, they consisted of the same elements, namely: statistical, logical and biological aspects, as well as practical consideration depending upon the intended used of the models and forest condition being studied. And so, the discussion on model evaluation in this study covers these three criteria.

Ideally, a model should also be evaluated using independent data, but such data were not available in this study without adversely affecting the size of sample. There seem to be differences in views among growth modellers regarding the necessity for model evaluation with independent data, the suitability of the term independence if data are partitioned for the purpose of model building and model evaluation.

3.3.1. Statistical and graphical analysis

Various functional forms fitted using the SAS procedures as indicated in section 3.2.2, required different criteria in evaluations. For the least-squares method, which involves minimizing the error sum of squares, the basic assumption is that the errors are independent, normally distributed with zero mean and homogenous variance. The first attempt in evaluating the models was checking the validity of these modelling assumptions.

A. Parameter estimations by the least-squares method

Checking model assumptions

The independence of errors could be inspected by plotting the residuals against the sequence in which observations were recorded (UOR, 1994). Positive correlation leads to a slowly varying pattern in which positive residuals are grouped with positive residuals and negative residuals with negative ones. While this method provides a useful way for detecting the extent of serial correlation, the procedure becomes tedious when the numbers of data are large and re-measurements are many. PROC REG in SAS provides Durbin-Watson d statistic; which can help to test whether or not the errors are correlated. This statistic is calculated as :

$$d = \sum_{i=2}^{n} (\hat{E}_i - \hat{E}_{i-1})^2 / \sum \hat{E}_i^2$$

The value of d will close to 0 ($d \approx 0$) if the residuals are perfectly correlated positively; if close to 4 ($d \approx 4$) then perfect negative correlation occurs; close to 2 ($d \approx 2$) shows that there is no serial correlation.

The problem of autocorrelation affects the efficiency of the least-squares method for parameter estimation. Positive correlation tends to cause the estimate of the error variance to be too small, and so confidence intervals are too narrow and a true null hypothesis is rejected with a higher probability than the stated significance level. Negative correlation tends to cause the estimate of the error to be too large, and so, confidence intervals are too wide and the power of significance tests is reduced.

A difficulty which may arise when conducting this test is in determining the value of the Durbin-Watson statistic to be considered close enough to 2, especially for a large number of observations which preclude the use of tabulated DW statistic to compare with the calculated DW. For this reason, the DW statistics presented in the result sections (Chapter 4) were used as ranking only when examining models in addition to other statistical and graphical measures.

Homogeneity of variance can be examined by plotting the residuals (Y_{act}- Y_{pred}) against predicted values to detect any pattern which indicates non-constant variance. Figure 3.1 shows some examples of residual patterns and distributions (redrawn from Alder, 1995).

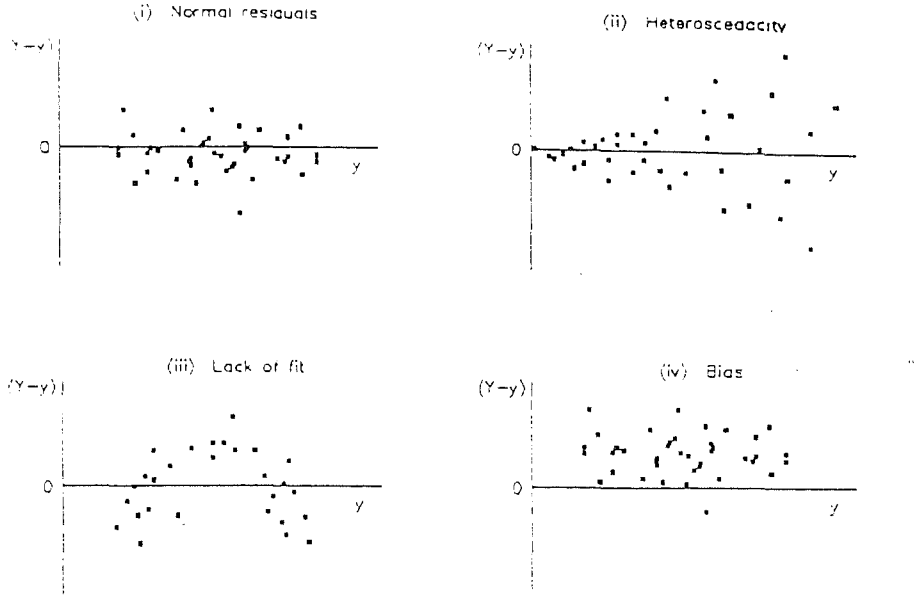


Figure 3.1. Some examples of residual patterns and distributions which may occur in fitted models.

The validity of the assumptions for normal distribution of errors with zero mean can also be examined using the univariate procedure in SAS :

1. The values of skewness, kurtosis, and mean of residuals can be used to evaluate the validity of underlying assumptions. If population skewness represented by m_3 and kutosis by m_4, accordingly,

$$m_4 > m_3^2 - 2$$

A theoretical normal distribution has zero skewness and kurtosis. However, this distribution may not exist in many real life cases. The tendency for distributions to have a larger magnitude of deviation in one direction (positive/negative) are commonly found in plant growth. Skewness reflects the tendency of the deviations to be larger in one direction than in the other, and its value can be positive or negative and is unbounded. Kurtosis, a measure of heaviness of the tail, has the value between –2 and positive infinity. Both sample skewness and kurtosis are calculated using the following formulas :

$$\text{Skewness} = n/(n-1)(n-2) \sum_{i=1}^{n} (x_i-\bar{x})^3 / S^3$$

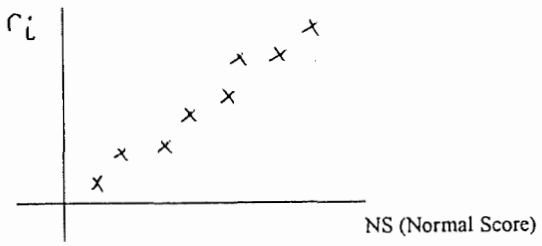
$$\text{Kurtosis} = n(n+1)/(n-1)(n-2)(n-3) \sum_{i=1}^{n} (x_i-\bar{x})^4/S^4 - 3(n-1)(n-1)/(n-2)(n-3)$$

A good model should have the value for the mean of residuals and skewness close to zero. Other statistics such as standard deviation and residual range were also used as criteria for model comparison.

2. This procedure also provides a measure for testing the normality assumption, in this case a null hypothesis test that residuals are normally distributed. The Shapiro-Wilk test (Prob <W) is used for sample sizes < 2000, and the Kolmogorov test (Prob>D) for sample sizes > 2000. The value of W must be greater than zero and less than or equal to one, small value of W leading to the rejection of the null hypothesis of normality. The value of Prob >D will appear < 0.01 or > 0.15 if the modified Kolmogorov statistic is sufficiently large or small.

3. Another way to check the validity of normality assumption is examining normal probability plots of the residuals (plots of residuals against standard normal distribution (see Figure 3.2; redrawn from UOR, 1994).

If the normality assumption is valid, the following type of graph will result



If the normality assumption is not valid, some possible departures that may be observed are:

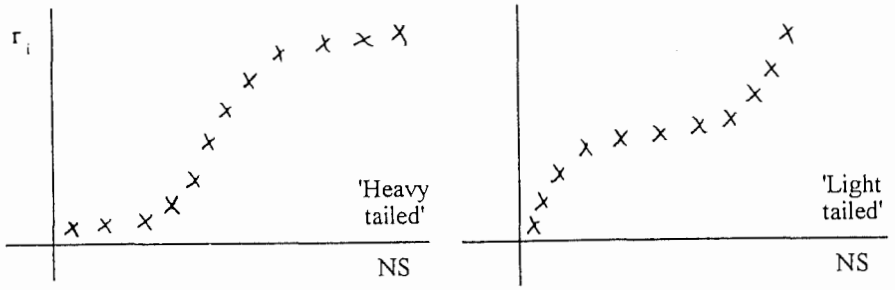


Figure 3.2. Plots of residuals against standard normal distribution, to examine the validity of assumptions for normal distribution of the error.

When the validity of model assumptions has been checked in this way, there are further tests of adequacy of a model to be examined. Residual mean squares (RMS) and coefficient of determination (R^2 or adjusted R^2) have been suggested and widely used to justify model quality. However, since the nature of data used in this study came from successive re-measurements (subject to autocorrelation) and some explanatory variables may be collinear, the variance (RMS) may be under estimated. R^2 does not seem meaningful for non-linear regression model (Ratkowsky, 1990). Vanclay (1994b) also demonstrated inappropriateness of considering R^2 for assessing model quality. A yield form will result in a higher R^2 than its corresponding growth form, and the more variables added to the model, the higher the R^2 obtained. In the case of increment model, basal area increment will have a higher R^2 than its corresponding diameter increment. For this reason, R^2 was not used to asses adequacy of the model in this study. RMS was used for ranking only, emphasis being given to the examination of the magnitude of the residual variance.

Outliers and influential observations

Outliers are data points which are apparently anomalous (UOR, 1994) and can cause heteroscedasticity (non-constant variance). In this study, an observation was defined as an

outlier, if it had the value of random normal deviate (RND = [residual/square root of residual mean squares]) greater than 3.5. The value of RND = 3.5 was chosen by referring to a standard normal distribution and considering the spread of the data used for this study. In a normal distribution, respectively about 68 %, 95 %, and 99.7 % of the population lie between one, two, and three standard deviation of the mean (SAS Inc., 1995). A normal curve with ordinate Y and axes z , where $Y = (1/\sqrt{2\pi}) \exp(-\frac{1}{2} z^2)$ and $z = (X-\mu)/\sigma$; then z is said normally distributed with mean zero and variance one (Spiegel, 1961). The area between z equal ± 1, ± 2, and ± 3 are equal to 68.27 %, 95.45 %, and 99.73 % respectively to the total area which is one. Hence, based on these criteria, the proportion of the data points that have the value of RND>3.5 is small if the data follow a normal distribution. In box plot obtained through UNIVARIATE procedure in SAS, observations with RND>3.5 can be recognized as an asterisk (*) with their quantities shown in stem-leaf plot.

An influential observation is one which has a value at extremes of the range of the data, it does not necessarily to have large residuals, but it may influence parameter estimates. The extreme value with a great effect on regression results is defined as an observation with large influence and high leverage.

The presence of these kinds of observation was checked during preliminary data analysis and in the process of modelling, through inspection of various graphical plots, then checking and re-checking possible error in the data sets or in model formulation.

Other aspects

Apart from the above criteria, both linear and non-linear models were also examined using some other statistical measures available in SAS for each of the three different procedures.

Linear model with PROC REG

Apparent problems that may arise from the nature of the data used in this study, were auto-correlation and multicollinearity. Problems associated with correlated data and ways for detecting auto-correlation have been explained in earlier paragraph of this chapter. Multicollinearity arises when there is near-linear dependency among the vector of explanatory variables (Wetheril, 1986). COLLIN and VIF options available in PROC REG were used to detect the existence of collinearity problems in the data for this study. The COLLIN option

prints Eigenvalue, condition index, and the proportion of the variance of the estimate accounted for by each principal component for each explanatory variable. Condition indices are the square roots of the ratio of the largest eiginvalue to each individual eigenvalue. The data are considered ill-conditioned if the largest condition index is large, and may have a fair amount of numerical error if this index is extremely large, as explained below. The VIF option prints variance inflation factors, which are measures of the inflation of variances of the parameter estimates due to the existence of collinearity among explanatory variables. There are no formal criteria for both COLLIN and VIF on how large these measures need to be to consider them large enough to affect the predicted value. For this reason, arbitrary values for the largest condition index and variance inflation factor suggested by Wetheril (1986) were used in this study as a guide for detecting the severity of multicollinearity problem. However, multicollinearity among variables is sometimes unavoidable in tree growth modelling, and so these measures too, were used as ranking only when comparing models. The value of these measures should not be greater than 100 for largest condition index; and or 10 for variance inflation factor. When multicollinearity occurred, the model was re-fitted by excluding variable with condition index >100, and the analysis was done by comparing the two models to see changes in parameter estimates and the fit of the models. If the fit was not better than before a variable was removed, the choice was then between the reduction in goodness of fit or tolerating the existence of multicollinearity. As explained earlier in this chapter, the final (linear) model was selected using various statistical criteria, as well as logical and biological aspects.

Non-linear model with PROC NLIN

The differences in least-squares estimation between linear and non-linear models, require different criteria in assessing model quality in addition to the basic assumptions that have to be met for least-squares method.

The parameter estimates for a linear model are unbiased, normally distributed, and have the minimum possible variance, while non-linear model achieve this property only asymptotically, that is, as a sample size approaches infinity (Ratkowsky, 1983). Checking asymptotic standard errors of parameter estimates and the corresponding confidence interval is necessary to determine whether an explanatory variable evidently has a significant effect on the response variable. Parameter estimates are retained if the upper and lower limits of the confidence interval have the same signs at a defined significant level (in this case was at 5 % level). High parameter correlation sometimes indicates over-parameterization (Ratkowsky,

1990), and so the asymptotic correlation matrix needs to be inspected. A low parameter correlation is desirable.

Least-squares estimates of the parameter in a linear model are determined from explicit mathematical expression, while those for a non-linear model are obtained through iteration, which requires a set of initial parameter estimates (Ratkowsky, 1983). The ability to converge in non-linear models depends very much on the parameterization of the model and on the initial value. The latter may require several re-runs in order to obtain the best possible estimates of parameters.

In order to select the best possible combination of competition and locality factors, firstly, each of these factors was added to the basic functional form, and its effect and the model fit were examined. Secondly, all additional terms were included in the model, and the significance of each term as well as the model fit was analyzed. Based on these results, various combinations of additional terms were tested, and final models were then selected using various statistical criteria, logical and biological aspects set out in this chapter.

B. Parameter estimations by maximum likelihood method

As stated earlier, three different procedures in SAS were used for fitting the equations to data : PROC REG for linear and linearized form of modified beta functions, PROC LOGISTIC for probabilistic function, and PROC NLIN for non-linear functions. The procedures for model evaluation described in the earlier paragraphs of section 3.3.1 apply to the linear (PROC REG) and non-linear (PROC NLIN) functions, since both procedures used least-squares method for parameter estimation.

The logistic procedure (PROC LOGISTIC) used maximum likelihood estimators to estimate the parameters. Model quality was assessed using the following criteria:

1. Pr>Chi-square, used to determine whether a variable should be included in the model (only variables which were evidently significant at $\alpha = 0.05$ were included),
2. Concordance, a measure of amount of population explained by the model,
3. AIC (Akaike Information Criterion) and SC (Schwartz criterion), used for comparing two or more models from the same data, the lower the value of these 2 statistics, the better is the model,
4. Score statistic tests of the joint significance of explanatory variables,

5. -2 Log L, shows the effect of explanatory variables based on -2 Log Likelihood; same as AIC and SC, the smaller the value of this measure, the better is the model.

The AIC, SC, and -2Log L are calculated using the following formulas :

$$-2 \text{ Log } L = -2 \Sigma_j w_j \log(\hat{p}_j)$$

where y_j is the response value of the j^{th} observation, $\hat{p}_j$ is estimate of $p_j=P(Y_j=y_j)$, and w_j is the weight of the j^{th} observation.

$$AIC = -2 \text{ Log } L + 2 (k+s)$$

where k is number of ordered value of the response, and s is number of explanatory variables.

$$SC = -2 \text{ Log } L + (k+s) \log (N)$$

3.3.2. Logical and biological aspects

Some procedures suggested by Oderwald and Hans (1993) and Vanclay and Skovsgaard (1996) were used as a guide in examining the models from logical and biological points of view. For example:

1. whether variables included or excluded from the model agree with expectation,
2. whether or not sign and magnitude of the parameter estimates conform to the logic and existing knowledge of forest growth or characteristics of the forest under study.
3. whether or not a model can be extrapolated reasonably,
4. whether or not possible contradictions within a model has been eliminated.

3.3.3. Criteria for selection of final models

Various functional forms and ways of species grouping for PT. ITCI data were examined jointly (see steps 1 to 7 in section 3.2.1). These models, as stated earlier, were fitted to data using three different procedures, and so different criteria (see section 3.3.1) were applied in examining each functional form. The final model for each species groups and data sets were selected by examining all criteria described in earlier sections of this chapter. The main consideration was given, however, to the basic assumption of parameter estimations. The closer a model is to meet the underlying assumption, the more preferred is the model. The final models selected for each data set (PT. ITCI, PT. INHUTANI I, and the combined PT.

ITCI/PT. INUTANI I data) did not imply the best models in absolute terms, but the models which were found best, represent growth characteristic of the forest under study, within the limits of available information and various approaches examined during this study.

Results of these modelling are presented and discussed in the following chapter.

CHAPTER 4
RESULTS AND DISCUSSION

Various ways of grouping species with similar tree growth trajectories were explored and different modelling techniques to characterize these trajectories were identified, in order to obtain the best possible tree diameter growth models from among the functional forms tested for the forest under study. Statistical, logical, and biological aspects, as well as practical considerations are the common criteria used in evaluating the quality of each model. While meeting all these criteria to a satisfactory degree, as explained more fully later, remains central to justifying the worth of each model, researchers often encounter difficulties when some factors limit their ability to meet all these criteria jointly. For example, the nature of the system being modelled, resources available to build the model, and state of growth modelling research for the particular system being modelled are all aspects to be accorded due emphasis. There could be a case where a model is logically and biologically sound, but apparently imprecise from a statistical point of view. In this situation, acknowledging the merits and drawbacks of the model is important, while appreciating that model construction has value in aiding understanding of the system being modelled, a main outcome is likely to involve providing insights into what further research is necessary.

This chapter presents and discusses the results of growth modelling carried out in this research project. It consists of two distinct sections :

1. results of modelling PT. ITCI, PT. INHUTANI I, and combined PT. ITCI/PT. INHUTANI I data;
2. discussion on species grouping, the apparent success or failure of the growth models examined and why certain models were finally selected, comparison between the selected models for PT. ITCI and other individual tree models developed for Indonesia's tropical rain forests, strengths and weaknesses of the selected models, insights gained from studying these particular forests and what further research is required.

As stated in Chapter 3, modelling effort was begun using PT. ITCI data; hence, the most detailed discussion pertains to the modelling of PT. ITCI data. Furthermore, the growth equation used for modelling PT. INHUTANI I and combined PT. ITCI/PT. INHUTANI I data was a modified form of Equation [7], which has been fully examined when modelling PT. ITCI data alone.

4.1. RESULTS

4.1.1. Modelling PT. ITCI data

The following sections present results of fitting various functional forms to several sets of species groups derived during this study (see steps 1 to 7 in section 3.2.1 of Chapter 3). As explained earlier in Chapter 3, modelling in 4.1.1.1 and 4.1.1.2 used data covering measurement periods from 1976 to 1990, while the data used for 4.1.1.3 and 4.1.1.4 include measurement records up to 1993. Stand attributes included in equations in sections 4.1.1.1 and 4.1.1.2 were calculated on a plot basis and converted to per hectare values, whereas for equations in 4.1.1.3 and 4.1.1.4, stand attributes were calculated on a sub-plot basis.

4.1.1.1. Fitting linear models and modified beta functions to 8 species groups

A. Linear model

A linear model comprising initial size, stand attributes and locality factors as explanatory variables was used to characterize annual diameter increment for PT. ITCI data, with procedures described in section 3.2.2 of Chapter 3. The following two combinations of initial size, stand attributes and locality factors were examined.

[1] $\ln d_i = \beta_0 + \beta_1 d + \beta_2 d^2 + \beta_i$ (stand attributes) + β_j (locality factors)

[2] $\ln d_i = \beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i$ (stand attributes) + β_j (locality factors)

where :

G, G>d, $(G_{>d})/\ln (d+1)$, alt, lov, and geom were the stand attributes and locality factors in various combinations included in the equations.

Results of fitting Equations [1] and [2] in the form of explanatory variables selected for each species group and their statistical measures obtained from the SAS univariate procedure are presented in Tables 4.1 to 4.4; the Durbin-Watson statistics, largest condition indices and variance inflation factors, are in Table 4.5. Graphical plots of growth trends are shown in Figures 4.1 and 4.2, whereas the complete SAS output from fitting both Equations [1] and [2] for each of eight species group are in diskette form (Appendix 4.1).

Both Equations [1] and [2] did not exhibit skewing of residuals for all slower growing species groups, slightly skewed residuals for Groups SF and UF, while the other two groups

(LF and MF) showed clear negative skewing of residuals. Initial size variables (d, d^2, ln d) for some species groups were found not significant even at 10 % ($\alpha = 0.1$) level (see Tables 4.1 and 4.3). Their coefficients, however, showed logical signs in terms of current knowledge about tree growth, except Group MS. The Group MS had a positive sign for the coefficient for variable d^2 (Equation [1]) or d (Equation [2]), which resulted in continuous increase of growth trends and not tenable for the concept of tree growth (Figures 4.1 and 4.2). For Group UF, variables d^2 of Equation [1] and d of Equation [2] did not show any considerable effect on the response variables, but their signs were negative (which is logically acceptable). However, the values of their coefficients were too small (negligible), and this resulted in continuous increase of growth trends.

Table 4.1. Selected explanatory variables and the parameter estimates for diameter increment functions of eight species groups for PT. ITCI data, obtained from fitting Equations [1].

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES AND ADJUSTED R^2									
	Int.	d	d^2	G	$G_{>d}$	$G_{>d}$/ ln(d+1)	SQ	alt	lov	R^2
LF	-.30	.02	$-1*10^{-4}$	-.02	-	-	.42	-.17	-	.18
LS	-1.52	$.003^{NS}$	$-3*10^{-5NS}$	-	-	-	-	-.04	.21	.02
MF	-.85	.04	$-5*10^{-4}$	-.02	-	-	.54	-	-	.11
MS	-1.38	$.01^{NS}$	-	-	-.01	-	-	-.08	.26	.08
SF	-2.31	.14	$-2*10^{-3}$	-	-	-	-	-	-	.04
SS	-1.92	$.03^{NS}$	$-4*10^{-4NS}$	-	-	-.03	-	-	.14	.02
UF	-0.37	.01	$-1*10^{-5NS}$	-.002	-	-	.64	-.17	-	.14
US	-1.71	.02	$-1*10^{-4}$	-	-	-	.15	-.13	.14	.05

NS : not significant; else, significant at least at $\alpha = 0.05$

Table 4.2. Statistical measures extracted from univariate output for ($\ln d_{iact}$-$\ln d_{ipred}$), for the equations with explanatory variables in Table 4.1

SPECIES GROUPS	N (no. of obs)	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF	2990	0.8269	-0.8616	1.0733	6.4933
LS	2837	0.8089	-0.3552	0.2453	6.6128
MF	1094	0.8923	-0.8647	0.5226	5.2916
MS	2249	0.8246	-0.3598	0.0034	5.5155
SF	218	0.9153	-0.5810	0.6343	5.0196
SS	827	0.8113	-0.2158	-0.0413	5.6056
UF	2595	0.9233	-0.4702	0.0850	6.8577
US	3229	0.8799	-0.2326	-0.1400	5.8404

Table 4.3. Selected explanatory variables and the parameter estimates for diameter increment functions of eight species groups for PT. ITCI data, obtained from fitting Equations [2].

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES AND ADJUSTED R^2									
	Int.	d	ln d	G>d	$G_{>d}$/ ln(d+1)	SQ	alt	lov	geom	R^2
LF	-2.35	-.01	.86	-.03	-	.33	-.15	.10	-	.19
LS	-2.45	-.01	.38	-	-	-	-.04	.21	-	.02
MF	-3.19	-.03	1.22	-.02	-	.47	-	-	-	.12
MS	-2.01	-	$.28^{NS}$	-.01	-	-	-.08	.26	-	.08
SF	-7.89	-.10	3.21	-	-	-	-	-	-	.04
SS	-2.90	$-.02^{NS}$	$.58^{NS}$	-	-.03	-	-	.13	-	.02
UF	-1.39	$-2*10^{-4NS}$	$.18^{NS}$	-	-	.60	-.18	.14	-	.12
US	-2.39	$-.004^{NS}$	.43	-	-	.16	-.12	-	-.11	.06

NS : not significant; else significant at least at $\alpha = 0.05$

Table 4.4. Statistical measures extracted from univariate procedure for ($\ln d_{iact}$-$\ln d_{ipred}$), for the equations with explanatory variables in Table 4.3

SPECIES GROUPS	N (no. of obs)	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF	2990	0.8232	-0.8671	1.0840	6.4512
LS	2837	0.8076	-0.3506	0.2606	6.6510
MF	1094	0.8891	-0.8746	0.5596	5.2352
MS	2249	0.8248	-0.3597	0.0060	5.5188
SF	218	0.9154	-0.5850	0.6586	5.0169
SS	827	0.8114	-0.2155	-0.0440	5.5985
UF	2595	0.9305	-0.4103	0.0718	6.8257
US	3229	0.8783	-0.2349	-0.1354	5.8332

Table 4.5. Durbin-Watson (DW) statistic, largest condition index (COLLIN) and variance inflation factor (VIF) for Equations [1] and [2].

SPECIES GROUP	EQUATION [1]			EQUATION [2]		
	DW	COLLIN	VIF	DW	COLLIN	VIF
LF	1.326	19.658	12.651	1.329	67.918	11.756
LS	1.432	16.348	9.927	1.438	70.235	14.913
MF	1.154	28.843	18.829	1.159	106.670	19.590
MS	1.405	13.377	1.630	1.405	28.271	1.632
SF	0.889	37.305	29.738	0.895	134.332	30.643
SS	1.466	45.913	32.234	1.466	168.671	33.909
UF	1.292	15.333	7.897	1.282	59.212	9.032
US	1.350	14.409	8.140	1.353	66.150	9.149

Figure 4.1. Growth trends of 8 species groups, drawn from Equation [1].

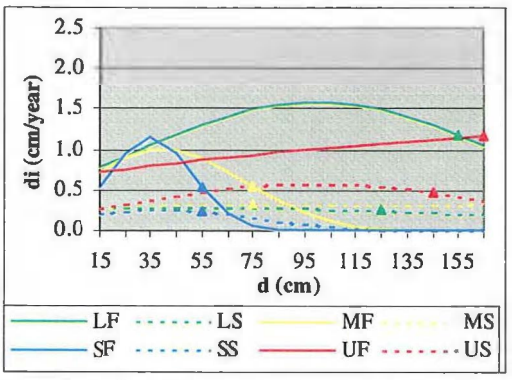
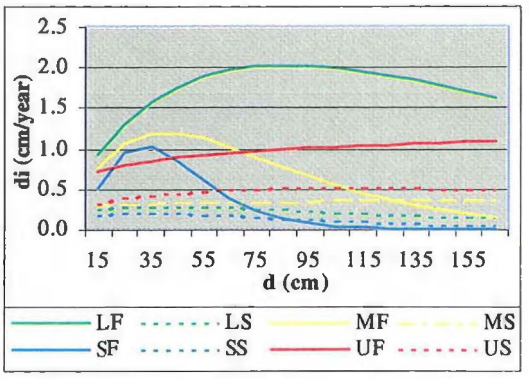


Figure 4.2. Growth trends of 8 species groups, drawn from Equation [2]



Note : Δ shows the maximum of data range (tree diameter) used to fit Equations [1] and [2]

B. Modified beta function

A linear form, e.g. Alder (1996), of a modified beta function, e.g. Vanclay (1989a), incorporating stand attributes and locality factors which were included in Equations [1] and [2], was fitted to each of eight species groups (Equation [3], see section 3.2.2 of Chapter 3).

[3] $\ln(di/(dmax-d)) = f(\text{stand attributes, locality factors}) + c \ln d$

Results of fitting Equation [3] are summarised in Tables 4.6 and 4.7; graphical plots of growth trends are shown in Figure 4.3; while the complete SAS outputs are presented in diskette form (Appendix 4.2). Examination of residuals indicated tendencies similar to Equations [1] and [2] for Groups LF and MF, in that clear negative skews of residuals were found. Other groups did not clearly exhibit skewness of residuals.

Table 4.6. Selected explanatory variables and the parameter estimates, Durbin-Watson (DW) statistic, largest condition index (COLLIN) and variance inflation factor (VIF) for eight species groups of PT. ITCI data, obtained from fitting Equation [3].

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES AND ADJUSTED R^2								DW	COLLIN	VIF
	Int.	G	$G_{>d}$	SQ	alt	lov	Ln d	R^2			
LF	-8.18	-	-	.36	-.17	.21	.84	.27	1.290	19.132	2.726
LS	-7.49	-	-	-	-.04	.21	.30	.05	1.423	18.034	1.559
MF	-7.30	-.02	-	.54	-	-	1.02	.17	1.159	41.743	15.151
MS	-7.89	-	-.01	-	-.08	.25	.86	.16	1.378	28.341	1.631
SF	-10.12	-	-	-	-	.36	2.04	.28	1.101	37.397	1.548
SS	-9.61	-	-.01*	-	-	.19	1.56	.21	1.429	28.804	1.237
UF	-7.45	-	-	.59	-.18	.17	.47	.15	1.261	20.009	2.399
US	-8.45	-	-	.20	-.14	.10*	.74	.13	1.314	20.949	2.714

* : significant at $\alpha = 0.1$; else, significant at least at $\alpha = 0.05$

Table 4.7. Statistical measures extracted from univariate output for $\{(\ln (d_i/(d_{max}-d)))_{act} - (\ln (d_i/(d_{max}-d)))_{pred}\}$, from fitting Equation [3] to each species group.

SPECIES GROUP	N (no. of obs)	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF	2989	0.8523	-0.6794	1.0568	8.4233
LS	2836	0.8064	-0.3593	0.2326	6.6460
MF	1093	0.8923	-0.8288	0.5283	5.3207
MS	2248	0.8375	-0.2438	0.3927	7.1297
SF	217	0.9129	-0.4447	0.5542	4.8910
SS	826	0.8282	-0.1745	0.0134	5.8984
UF	2594	0.9399	-0.3069	0.5435	9.2664
US	3228	0.8971	-0.1065	0.3380	8.1850

Note : d_{max} = observed d_{max} for species groups.

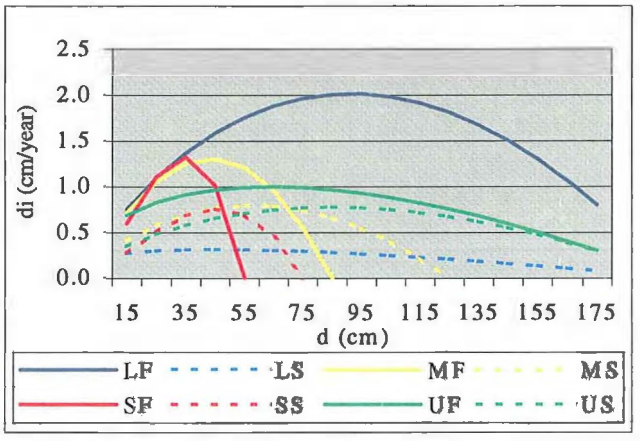


Figure 4.3. Growth trends of 8 species groups, drawn from Equation [3].

4.1.1.2. Fitting linear model, probabilistic, and modified beta functions to 4 species groups

Unsatisfactory results were obtained from fitting Equations [1] and [2]. Equation [3] performed better than the first two equations, but skewed residuals were clearly found for Groups LF and MF. Faster and slower growing species groups were then amalgamated, which resulted in four groups of L, M, S, and U. The same equations (Equations [1] and [3]) were fitted to the four species groups with additional explanatory variables to be examined. Another functional form (Equation [6]) was also fitted.

A. Linear model

The linear equation next used was a further modification of Equation [2], where stand attributes incorporated in the equation included the logarithm of these attributes, while locality factors did not include the variable lov (see section 3.2.2 of Chapter 3).

[4] $\ln d_i = \beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i (G, G>d, \ln G, \ln G>d) + \beta_j (SQ, alt, geom)$

Results of fitting Equation [4] to all species together and each of four species groups are summarized in Tables 4.8 to 4.10; Figure 4.4 and the complete SAS outputs are in diskette form (Appendix 4.3). This equation resulted in improved and reasonable residual patterns for all species groups. The residual ranges, however, were larger than in Equations [1] and [2] for the eight species groups, and multicollinearity was found to occur in each species group (see Table 4.10).

Table 4.8. Selected explanatory variables and the parameter estimates for diameter increment functions of all species together and four species groups for PT. ITCI data, obtained from fitting Equation [4].

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES AND ADJUSTED R^2								
	Int.	d	Ln d	Ln G	ln $G_{>d}$	SQ	alt	geom	R^2
ALL SPECIES	-1.95	-.01	.60	.59	-.88	.37	-.12	-.07	.13
L	-2.55	-.01	.58	-	-	.45	-.16	-	.09
M***	-0.52	-	.38*	-	-.58	.60	-.13	-	.22
S**	-2.45	-.04*	1.44	-	-.81	-	-	-	.12
U	-2.07	-.01	.55	.99	-1.24	.30	-.18	-	.11

* : significant at $\alpha = 0.1$; ** : intercept significant at $\alpha = 0.1$; *** : intercept not significant; else, significant at least at $\alpha = 0.05$

Table 4.9. Statistical measures extracted from univariate output for ($\ln d_{iact}$-$\ln d_{ipred}$), from fitting Equation [4] to each species group.

SPECIES GROUP	N (no. of obs)	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
ALL SPECIES	16040	0.9342	-0.3563	-0.0568	7.5043
L	5827	0.9176	-0.4300	0.0682	7.1594
M	3343	0.9447	-0.3746	-0.0902	6.2043
S	1045	0.9495	-0.0499	-0.0002	6.4616
U	5825	0.9318	-0.2795	-0.1631	6.4185

Table 4.10. Durbin-Watson (DW) statistic, largest condition index (COLLIN) and variance inflation factor (VIF) for Equation [4].

SPECIES GROUP	DW	COLLIN	VIF
ALL SPECIES	1.134	198.230	25.132
L	1.091	58.551	11.608
M	1.109	124.227	21.338
S	1.266	159.363	32.360
U	1.171	225.638	32.676

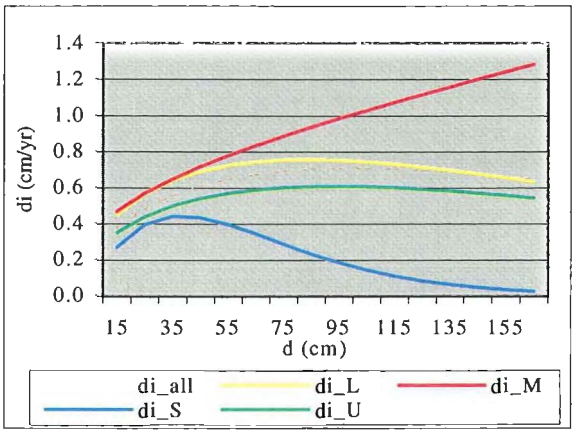


Figure 4.4. Growth trends of 4 species groups, drawn from Equation [4].

Both Figures 4.2 (8 species groups) and 4.4 (4 species groups) were drawn using the same basic functional form (Equation [3.2] in Chapter 3, but used slightly different stand attributes and locality factors. This difference, added by disproportionate of the data between faster and slower growing species in most groups might have caused the growth patterns were somehow distorted when faster and slower growing species groups were combined.

B. Modified beta function

The following equation (a further modification of Equation [3]) was fitted to all species together and each of four species groups (see 3.2.2 of Chapter 3).

[5] Ln (di/(dmax-d)) = f (d, ln d, G, G>d, ln G, ln G>d, SQ, alt, geom) + c ln d

Results of fitting Equation [5] are presented in Tables 4.11 to 4.13; and Figure 4.5; extracted from Appendix 4.4 (in diskette form).

Table 4.11. Selected explanatory variables and the parameter estimates for all species together and four species groups for PT. ITCI data, obtained from fitting Equation [5]

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES AND ADJUSTED R^2									
	Int	G	Ln G	$G_{>d}$	Ln $G_{>d}$	SQ	alt	Geom	Ln d	R^2
ALL SPECIES	-7.03	-	1.67	-	-.1.82	.35	-.10	-.17	.47	.15
L	-9.74	-	.84	-.04	-	.37	-.13	-	.61	.17
M	-6.56	-	-	-	-.58	.60	-.12	-	1.01	.27
S	-9.20	-.02	-	-	-	.37	-	-	1.67	.25
U	-6.68	-	-.39	-	-	.36	-.16	-.06	0.60	.14

Note : all variables were significant at least at α =0.05.

Table 4.12. Statistical measures extracted from univariate output for$\{(\ln(d_i/(dmax-d)))_{act} - (\ln(d_i/(dmax-d)))_{pred}\}$, for fitting Equation [5] to each species group.

SPECIES GROUP	N (no. of obs)	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
ALL SPECIES	16040	1.0807	-0.0201	0.2770	9.7830
L	5827	0.9121	-0.4532	0.2169	9.0029
M	3343	0.9570	-0.2897	0.0425	7.8932
S	1045	0.9592	-0.0482	0.0416	6.9896
U	5825	0.9371	-0.2473	-0.0379	8.2092

Table 4.13. Durbin-Watson (DW) statistic, largest condition index (COLLIN) and variance inflation factor (VIF) for Equation [5].

SPECIES GROUP	DW	COLLIN	VIF
ALL SPECIES	0.850	186.297	25.118
L	1.107	184.173	27.680
M	1.100	32.095	1.497
S	1.255	28.384	1.170
U	1.168	51.777	2.378

Equation [5] behaved similarly to Equation [4] as it resulted in reasonable residual patterns for all species groups, but with larger residual ranges compared to the same functional form for eight species groups (Equation [3]), except for Group U. A multicollinearity problem was found in the large tree species (Group L) and all species together (see Table 4.13).

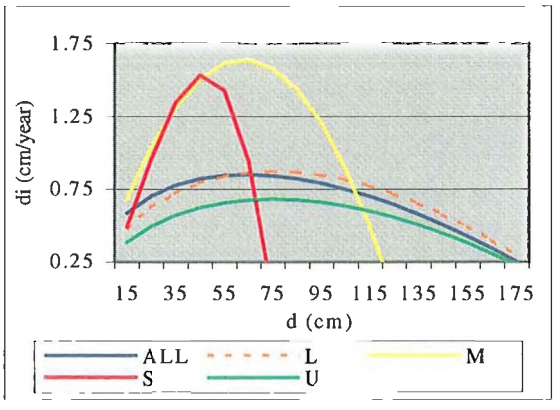


Figure 4.5. Growth trends of 4 species groups, drawn from Equation [5].

It can be seen from Figures 4.3 (8 species groups) and 4.5 (4 species groups), that the same tendency found in Figures 4.2 and 4.4 also occurred here where growth patterns were distorted when faster and slower growing species groups were combined.

C. Probabilistic function

A probabilistic function, as chosen by Vanclay (1991d), for example, was used to model the probability of a tree completing growth of an integer number of cm, in a certain year from a certain diameter, for all species together and each of four species groups, using the procedure described in section 3.2.2. This was evaluated using criteria explained in section 3.3 of Chapter 3.

[6] $P = (1+\exp(-(\beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i (G, G>d, \ln G, \ln G>d) + \beta_j (SQ, alt, geom)))^{-1}$

where P is $P\{Int[d_1+(d_2-d_1)/(t_2-t_1)] > Int[d_1]\}$

Results of fitting Equation [6] to all species together and each of four species groups are presented in Tables 4.14 and 4.15, which summarise Appendix 4.5 (in diskette form), and shown as a graphical growth trend in Figure 4.6.

Table 4.14. Selected explanatory variables and the parameter estimates for all species together and four species groups for PT. ITC1 data, obtained from fitting Equation [6].

SPECIES GROUP	PARAMETER ESTIMATES FOR SELECTED EXPLANATORY VARIABLES						
	Int.	d	Ln d	Ln G	$G_{>d}$	SQ	alt
ALL SPECIES	-4.75	-.02	1.21	.59	-.05	.57	-.19
L	-2.91	-02	1.14	-	-.02	.57	-.18
M	-2.23	$-.01^{NS}$	.76*	-	-.04	.97	-
S	-13.56	-.12	4.14	1.68	-.13	-	-
U	-2.74	-.02	.97	-	-.03	.31	-.25

NS : not significant; * : significant at α=0.1; else, significant at least at α=0.05

Table 4.15. Values of Akaike Information Criterion (AIC), Schwartz Criterion (SC), and –2 Log L; for selected set of variables for each species group, obtained from fitting Equation [6].

SPECIES GROUP	AIC	SC	-2 Log L	CONCORDANT
ALL SPECIES	24041.275	24096.704	24027.275	0.646
L	8674.413	8715.459	8662.493	0.633
M	4768.855	4800.296	4758.855	0.679
S	1376.183	1402.087	1366.183	0.679
U	9003.127	9045.191	8991.127	0.613

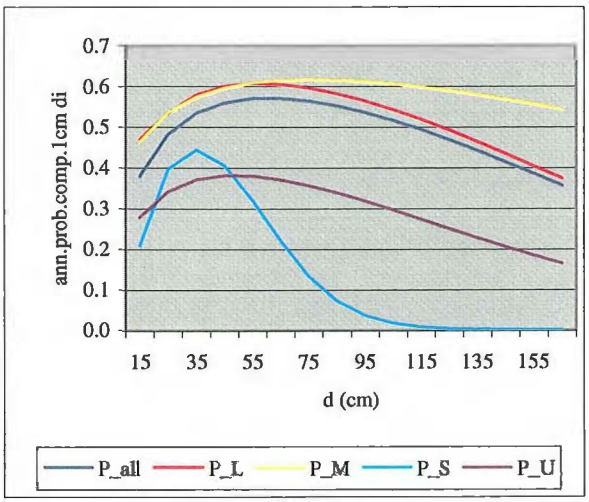


Figure 4.6. Growth trends of 4 species groups, drawn from Equation [6].

Explanatory variables in Table 4.14 were selected through comparing the values of AIC, SC, and –2 Log L and concordant, among sets of variables examined. Variable d for the medium tree species group (Group M) was not found to be significant, but its sign did not contravene logical and biological concept of tree growth.

4.1.1.3. Fitting Gompertz projection equations to 8 species groups and all species/ groups as dummy variable

The following ways of fitting Equation [7] was a further step in identifying the best possible grouping of species and diameter growth models for the second data set of PT. ITCI, proceeding in steps 3 to 5 in section 3.2.1 of Chapter 3.

[7] $d_2 = \text{Exp}(\text{Ln}(d_1).e^{-\beta(t2-t1)} + \alpha(1-e^{-\beta(t2-t1)}))$

A. Fitting Gompertz projection equation to 8 species groups

A first modified form of Equation [7] which incorporated stand attributes and locality factors, was fitted to each of eight species groups of PT. ITCI data (Equation [7.1]). Variables G_{sp}, G_{sp}>d, lov, alt, were the stand attributes and locality factors initially examined, the choice having been based on earlier findings that these variables were important in affecting diameter increment. Other variables such as tci, ci, SQ, and geom were then also included in the equations.

[7.1] $d_2 = \text{Exp}(\text{Ln}(d_1).e^{-f(\text{stand attributes, locality factors})(t2-t1)} + \alpha(1-e^{-f(\text{stand attributes, locality factors})(t2-t1)}))$

Results of fitting Equation [7.1] to the 8 species groups demonstrated reasonable patterns and distributions of residuals for all eight groups. The slower growing species groups, however, showed slightly less well balanced residual distributions than the faster growing ones. This can also be seen in Table 4.17 in that the slower growing species groups were found to have larger values of skewness and kurtosis than for the faster growing species groups.

The results also suggested that variables ci and tci were better representations of competition factors than G and $G_{>d}$ for faster growing species except Group SF. Variable lov proved to be an important factor affecting diameter growth except for Group SF, where no additional term was found to have significant effect. Parameter estimates and other statistical measures of selected equation for each of the 8 species groups, obtained from Equation [7.1] are summarised in Tables 4.16 and 4.17; graphical plots of residual patterns and distributions in Appendix 4.6a; graph of growth trend in Figure 4.7, while the complete SAS outputs from the equation selected for each of 8 species groups are in diskette form (Appendix 4.6b).

Table 4.16. Parameter estimates and residual mean squares (RMS), obtained from fitting the modified form of Equation [7.1] for 8 species groups for PT. ITCI data.

SPECIES GROUP	PARAMETER ESTIMATES							RMS
	α	β_0	β_1(tci)	$\beta_1(G_{sp>d})$	β_2(alt)	β_3(lov)	β_4(ci*tci)	
LF	5.252661	0.009681	0.002014	0	-0.000010	0.002348	-0.004071	1.1647
LS	4.850239	0.004953	0	0	-0.000002	0.000815	0	0.2637
MF	4.726099	0.013441	0.004195	0	0	0.004219	0	1.9774
MS	5.175559	0.004062	0	0	-0.000003	0.001031	0	0.2539
SF	4.648184	0.017005	0	0	0	0	0	1.8291
SS	4.491079	0.004172	0	-0.001642	0	0.001161	0	0.1662
UF	5.108535	0.009599	0.003036	0	-0.000008	0.003239	-0.011174	0.9546
US	5.155123	0.003794	0	0	-0.000004	0.001044	0	0.2749

Note : all variables were significant at 95 % confidence interval

Table 4.17. Statistical measures for residuals, obtained through SAS univariate procedure of fitting the modified form of Equation [7.1] for 8 species groups for PT. ITCI data.

SPECIES GROUP	N (number of observations)	MEAN	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RANGE (cm)
LF	2871	0.127471	1.070695	0.325607	1.455489	7.463416
LS	3233	0.088441	0.505589	0.453941	1.852947	3.950272
MF	1151	0.149601	1.396372	0.172048	0.790397	9.562150
MS	2209	0.090303	0.495351	0.272572	1.350666	3.703449
SF	213	0.232809	1.316880	0.106550	0.932669	8.180539
SS	1094	0.090701	0.396905	0.269939	1.511973	2.784904
UF	1219	0.117001	0.967955	0.518880	1.863765	7.170711
US	2961	0.108292	0.512764	0.609314	1.965701	3.782293

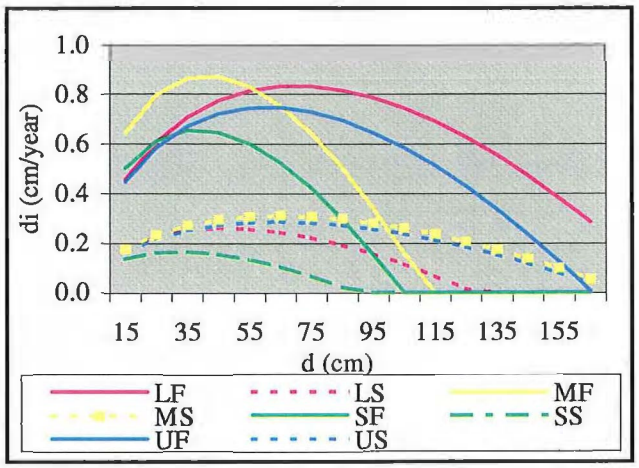


Figure 4.7. Growth trends of 8 species groups, drawn from Equation [7.1]

B. Fitting Gompertz projection equation to all species/groups as dummy variables

Equation [7] was next modified to the following form (Equation [7.2]), allowing each species group to have a different α value (maximum size). No additional terms were included in the equation, since earlier results (Appendix 4.7a) showed that species groups with large representations affected the apparent significance of certain variables although these variables may not be important for species groups with much smaller numbers of observations.

[7.2] $d_2 = \text{Exp}(\text{Ln}(d_1).e^{-\beta(t2-t1)} + (\alpha_{i\ldots j})(1-e^{-\beta(t2-t1)}))$,

where i.....j = species groups.

Table 4.18 presents a summary of results for fitting Equation [7.2], while full documentation is in Appendix 4.7b. Graphical measures of residual pattern and distribution are presented in Appendix 4.7c. A clear difference emerged from fitting the two Equations [7.1] and [7.2]: there was a much larger kurtosis value for Equation [7.2] than for Equation [7.1]. The values for parameter α for Groups MF and SF were found to be much larger than for the rest of the groups, even after checking using smaller starting values of α. This resulted in a growth trend where maximum size would not be achievable in reality as shown in Figure 4.8.

Table 4.18. Parameter estimates and other statistical measures obtained from fitting Equation [7.2] for PT. ITCI data.

PARAMETER ESTIMATES			OTHER STATISTICAL MEASURES	
α_1 (LF)	5.6013			
α_2 (LS)	4.5572		RMS	0.726
α_3 (MF)	6.7786		MEAN RESIDUAL	0.1070
α_4 (MS)	4.4387		STANDARD DEVIATION (cm)	0.8451
α_5 (SF)	6.4024		SKEWNESS	0.7219
α_6 (SS)	4.0264		KURTOSIS	5.4554
α_7 (UF)	5.6196		RESIDUAL RANGE (cm)	11.7928
α_8 (US)	4.2643			
β	0.0070			

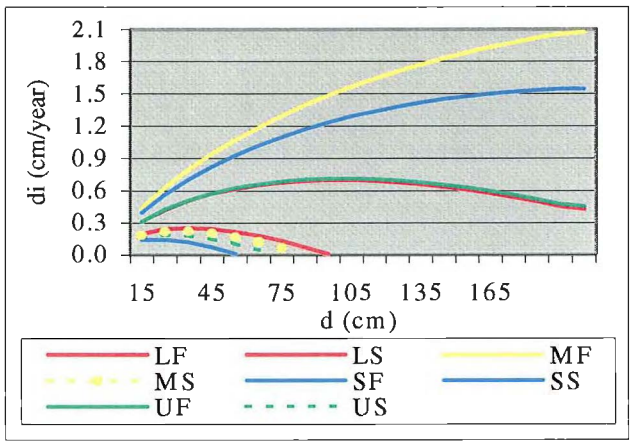


Figure 4.8. Growth trends of 8 species groups, drawn from Equation [7.2]

4.1.1.4. Fitting nonllinear Gompertz projection form and linear model to 4 species groups, and comparison between the two functional forms

A. Gompertz projection (non-linear) equation

The basic form of a Gompertz projection equation (Equation [7]) was modified to incorporate stand attributes and locality factors.

[7] $d_2 = \mathrm{Exp}(\mathrm{Ln}(d_1).e^{-\beta(t2-t1)} + \alpha(1-e^{-\beta(t2-t1)}))$

where β was expressed as a linear function of stand attributes (tci, ci, ci*tci) and locality factors (lov. alt, SQ, geom)

The modified form of Equation [7] was then fitted to four species groups, namely LUF, LMUS, MeSF, and SmaS. Stand attributes and locality factors found to have substantial effect

on the response variable in earlier modelling (section 4.1.1.3), were firstly included in the equation, then later the additions of variables geom (geomorphology) and SQ (site quality characteristics) individually and jointly were examined. Twenty equations were obtained from fitting the basic and modified forms of Equation [7], selected using criteria outlined in Chapter 3 (section 3.3). Ten equations were derived for Group LUF; three equations for each of Groups LMUS and SmaS, and four equations for Group MeSF. The corresponding parameter estimates and residual mean square (RMS) values are presented in Table 4.19. Other statistical measures, extracted from the output of the SAS univariate procedure, are in Table 4.20, while the complete outputs for running each of the 20 equations are included in diskette form (Appendix 4.8).

Table 4.19 shows that the faster growing species (Groups LUF and MeSF) resulted in a bigger number of suitable equation options than the slower growing species (Groups LMUS and SmaS). Checking distributions of the data for each species group indicated that faster growing species groups had bigger proportions of well represented species (species with number of observations >100); each of 14 % and 10 % for LUF and MeSF, 2 % and 3 % of the total number of species in the group for LMUS and SmaS respectively. Group LUF, which was dominated by Dipterocarps (mainly the genus *Shorea*), was found to produce the largest number of possible combinations of terms additional to the basic form. The distributions of the LUF group showed the least concentration of narrow ranges of data values for most explanatory variables examined, followed by Group MeSF. These distributions of data perhaps affected whether or not the effect of an explanatory variable for certain species group could be detected.

The major division of additional terms in the LUF group was the combination of ci or tci with two other variables, lov and alt. The choice between variables ci and tci in the equations was based on earlier results where the variable ci alone was found to have substantial effects in the absence of the variable tci. The same result was found between variables tci and $G_{sp>d}$ for Group MeSF, where variable $G_{sp>d}$ showed a considerable effect when variable tci was dropped from the equation.

Table 4.19. Parameter estimates and residual mean squares (RMS) of the basic and modified forms of Equation [7]

ADDED TERMS	PAREMETER ESTIMATES FOR EACH SPECIES GROUP AND COMBINATIONS OF ADDED TERMS								RMS
	α	β_0	β_1 (tci)	β_2 (ci)	β_3 ($G_{sp>d}$)	β_4 (alt)	β_5 (lov)	β_6 (ci*tci)	
Large and other faster growing species (LFUF)									
basic form	5.21336180	0.00951868	0	0	0	0	0	0	1.2329
Lov	5.28399170	0.00763275	0	0	0	0	0.00367628	0	1.1408
tci, lov	5.17217398	0.00673753	0.00235757	0	0	0	0.00391106	0	1.1258
tci, alt, lov	5.17623639	0.00922452	0.00229971	0	0	-0.000009321	0.00281343	0	1.1114
ci, lov	5.28399740	0.00815642	0	-0.00175504	0	0	0.00355224	0	1.1327
ci, alt, lov	5.28725599	0.01038876	0	-0.00167784	0	-0.000008571	0.00256329	0	1.1183
tci, lov, ci*tci	5.23940257	0.00700609	0.00225971	0	0	0	0.00361688	-0.00474087	1.1187
tci, alt, lov, ci*tci	5.24813989	0.00937360	0.00218823	0	0	-0.000008896	0.00256105	-0.00480457	1.1040
ci, lov, ci*tci	5.34190160	0.00805822	0	-0.00115526	0	0	0.00339335	-0.00286545	1.1305
ci, alt, lov, ci*tci	5.35286767	0.01021047	0	-0.00103594	0	-0.000008319	0.00240630	-0.00310804	1.1156
Large, medium, and other slower growing species (LMUS)									
basic form	5.01929571	0.00386819	0	0	0	0	0	0	0.2791
Lov	4.97951834	0.00351167	0	0	0	0	0.00141038	0	0.2697
alt, lov	4.97179431	0.00444582	0	0	0	-0.000003170	0.00096347	0	0.2684
Medium and small faster growing species (MeSF)									
basic form	4.85874765	0.01688332	0	0	0	0	0	0	2.0125
Lov	4.88606190	0.01378864	0	0	0	0	0.00368374	0	1.9745
tci, lov	4.71200955	0.01353361	0.00387490	0	0	0	0.00418037	0	1.9585
$G_{sp>d}$, lov	4.84664588	0.01472653	0	0	-0.00315449	0	0.00369043	0	1.9699
Small slower growing species (SmaS)									
basic form	4.45162827	0.00422323	0	0	0	0	0	0	0.1712
Lov	4.50966284	0.00371007	0	0	0	0	0.00108456	0	0.1686
$G_{sp>d}$, lov	4.49127289	0.00417080	0	0	-0.00164163	0	0.00116117	0	0.1662

Note : all variables were significant at 95 % confidence interval.

Table 4.20. Statistical measures for residuals (d_{2act}–d_{2pred}) for 4 species groups, obtained through the univariate procedure for basic and modified forms of Equation [7].

GROUP/ EQUATIONS	N	MEAN RESIDUAL	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
Large and other faster growing species (LUF)						
1. basic form	4090	0.119487	1.103761	0.529253	1.911058	9.157362
2. lov	4090	0.125440	1.060446	0.415175	1.510131	7.598471
3. tci, lov	4090	0.130615	1.052573	0.388024	1.522061	7.323373
4. ci, lov	4090	0.125893	1.056425	0.410567	1.525040	7.519119
5. tci, alt, lov	4090	0.127087	1.046012	0.378684	1.568379	7.426468
6. ci, alt, lov	4090	0.122376	1.049865	0.395092	1.553754	7.384536
7. tci, lov, ci*tci	4090	0.128855	1.049262	0.392287	1.543044	7.588954
8. ci, lov, ci*tci	4090	0.124720	1.055367	0.411268	1.525134	7.855945
*9. tci, alt, lov, ci*tci*	*4090*	*0.125254*	*1.042563*	*0.382568*	*1.562040*	*7.390094*
10.ci, alt, lov, ci*tci	4090	0.121166	1.048580	0.396029	1.538502	7.399048
Large, medium, and other slower growing species (LMUS)						
11. basic form	8403	0.096192	0.519430	0.479165	1.901601	4.215872
12. lov	8403	0.097586	0.510051	0.440034	1.727408	3.776004
13. alt, lov	*8403*	*0.096608*	*0.508939*	*0.454298*	*1.709901*	*3.706128*
Medium and small faster growing species (MeSF)						
14. basic form	1364	0.164214	1.408552	0.169458	1.081297	10.90322
15. lov	1364	0.163489	1.394587	0.153187	0.839912	9.683021
16. tci, lov	*1364*	*0.162605*	*1.388418*	*0.169003*	*0.829489*	*9.573077*
17. $G_{sp>d}$, lov	1364	0.163214	1.392462	0.157908	0.883912	9.673925
Small slower growing species (SmaS)						
18. basic form	1094	0.091699	0.403235	0.310457	1.714676	2.780053
19. lov	1094	0.092394	0.399699	0.301932	1.579701	2.734737
20. $G_{sp>d}$, lov	*1094*	*0.090719*	*0.396901*	*0.270055*	*1.511927*	*2.784865*

Among the 20 equations tested, the ones with the following additional terms, namely: tci, alt, lov, and ci*tci (Group LUF); alt and lov (Group LMUS); tci and lov (Group MeSF); $G_{sp>d}$ and lov (Group SmaS); were chosen as the best options (see no. 9, 13, 16, and 20 in Table 4.20). Criteria used to select these four equations included: RMS values (Table 4.19); statistical measures in Table 4.20; lack of bias evident in plots of residual patterns and frequency distributions of residual classes, normal probability plots, and asymptotic correlation matrices between parameters in the equations (Appendix 4.8). These equations were also all found to have the smallest RMS value. The criterion RMS, however, was used for ranking only, because of a lack of total independence among basic data.

In order to observe the reasonableness of the fits of the selected equations for individual species data, the equation for each species group was fitted to individual species comprising a reasonable number of observations, and plots of residuals against predicted values were produced (Appendix 4.10). The individual species considered here were the ones which had a minimum of 100 observations, except for Group SmaS which used only 45

observations because they were little represented. This empirical way of evaluating model fits was also found useful in examining further the appropriateness of the derived species groups. For examples *Hopea mengerawan* showed clear bias when the selected equation for Group LMUS was fitted just to its data (Appendix 4.11), but much less bias in it was shown when the LUF model was fitted to data for this species (Appendix 4.12). Transferring this species from Group LMUS to Group LUF resulted in substantial model improvement for both species groups (see Tables 4.20 and 4.22; and Appendices 4.8 and 4.9b).

The effect of geological aspects such as geomorphology (geom) and soil quality characteristics (SQ), expressed as dummy variables, were then examined. Geomorphology (variable geom) did not prove to be an important factor affecting diameter growth for all species groups. The variable for soil quality characteristics, expressed as better (SQ=1) and poor (SQ=0), was found to have an important effect only for Group LUF in the presence of the variable lov. For Group LMUS, this variable was significant but with a negative sign for the coefficient; while for the Group MeSF, the variable lov became non-significant when variable SQ was included in the equation. For this reason, two equations, one with variable lov and another with variable SQ, were fitted to each of the two latter groups. The parameter and RMS values of the final selected models for each group, including the equation with variable SQ for the three groups of LUF, LMUS, and MeSF, are presented in Table 4.21; other statistical measures obtained from the univariate procedure are in Table 4.22 and Appendix 4.9b).

By comparing the statistical measures in Table 4.22, and other criteria set out in section 3.3.1 of Chapter 3, such as the distribution of residuals, presence of outliers, normal probability plots, and asymptotic correlation matrix (see Appendix 4.9b), the following final equations were selected for each species group.

[7.a] $$d_{2LUF} = \text{Exp}(\text{Ln}(d_1).e^{-(0.00929+0.00253\ tci-0.00001\ alt+0.00228\ lov-0.00532\ ci*tci)\ (t2-t1)} + 5.23813\ (1-e^{-(0.00929+0.00253\ tci-0.00001\ alt+0.00228\ lov-0.00532\ ci*tci)\ (t2-t1)}))$$

[7.b] $$d_{2LMUS} = \text{Exp}(\text{Ln}(d_1).e^{-(0.00437-0.000003\ alt+0.00094\ lov)\ (t2-t1)} + 4.98469(1-e^{-(0.00437-0.000003\ alt+0.00094\ lov)\ (t2-t1)}))$$

[7.c] $$d_{2MeSF} = \text{Exp}(\text{Ln}(d_1).e^{-(0.01353+0.00387\ tci+0.00418\ lov)\ (t2-t1)} + 4.71201(1-e^{-(0.01353+0.00387\ tci+0.00418\ lov)\ (t2-t1)}))$$

[7.d] $$d_{2SmaS} = \text{Exp}(\text{Ln}(d_1).e^{-(0.00417-0.00164\ Gsp>d+0.00116\ lov)\ (t2-t1)} + 4.49127\ (1-e^{-(0.00417-0.00164\ Gsp>d+0.00116\ lov)\ (t2-t1)}))$$

where :

d_{2LUF}.....d_{2SmaS} are tree diameters in cm at time 2 by species groups; other variables are as stated in Chapter 3.

A measure of goodness of fit for the final selected equations in the form of graphical plots of residuals against predicted values and histograms of the frequency distribution of residuals are presented in Appendix 4.9a, while graphs of growth trends drawn from Equations [7.a-d] are shown in Figures 4.9a-b.

Table 4.21. Parameter estimates and residual mean squares (RMS) of the final model selected for each species group (includes equation with variable SQ for three groups of LUF, LMUS, MeSF).

SPECIES GROUP	PARAMETER ESTIMATES								RMS
	α	β_0	β_1 (tci)	β_2 ($G_{sp>d}$)	β_3(alt)	β_4 (lov)	β_5 (ci*tci)	β_6 (SQ)	
LFUF (*)	5.236938028	0.009665354	0.002501009	0	-0.000011142	0.001305087	-0.00516052	0.001330351	0.9799
(**)	5.238128247	0.009294471	0.002529272	0	-0.000009766	0.002275402	-0.005318468	0	0.9835
LMUS (**)	4.984690522	0.004371513	0	0	-0.000003456	0.000939302	0	0	0.2524
(***)	4.990562031	0.005122877	0	0	0.000005697	0	0	0.000449811	0.2542
MeSF (**)	4.712009546	0.013533605	0.003874904	0	0	0.004180371	0	0	1.9585
(***)	4.745153373	0.013223421	0.003731172	0	0	0	0	0.004857447	1.9280
SmaS	4.491272887	0.004170800	0	-0.001641629	0	0.001161170	0	0	0.1662

Note : all variables were significant at 95 % confidence interval.

Table 4.22. Statistical measures for residuals (d_{2act}-d_{2pred}) obtained through SAS univariate procedure for the final model selected for each species group (includes equation with variable SQ for three groups of LUF, LMUS, MeSF).

SPECIES GROUP	N	MEAN	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RANGE (cm)
LUF (*)	4273	0.129450	0.980699	0.311545	1.452704	7.206945
(**)		0.127640	0.982887	0.309510	1.464404	6.971707
LMUS (**)	8158	0.095890	0.493047	0.396129	1.549175	3.455983
(***)		0.095420	0.495012	0.410844	1.595694	3.816021
MeSF (**)	1364	0.162605	1.388418	0.169003	0.829489	9.573077
(***)		0.167889	1.376777	0.157881	0.845289	10.36513
SmaS	1094	0.090719	0.396901	0.270055	1.511927	2.784865

(*) : with variable SQ; (**) : without variable SQ for selected models; (***) : variable lov replaced by SQ.

Figures 4.9a-b. Growth trends for four species groups, drawn from Equations [7.a-d], assuming tci=0.8; alt=100 m a.s.l; ci=0.25 m^2/0.01 ha; and $G_{sp>d}$= 0.2 m^2/0.01 ha.

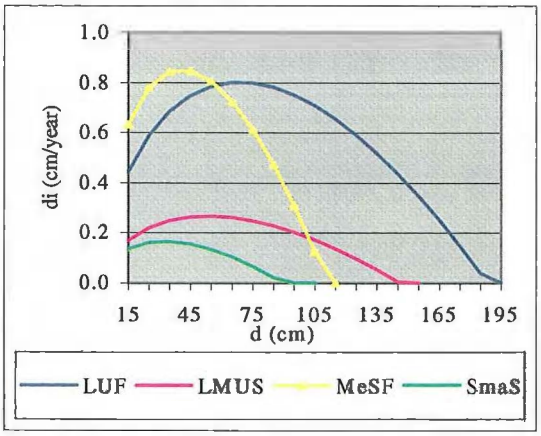


Figure 4.9a. logged plots

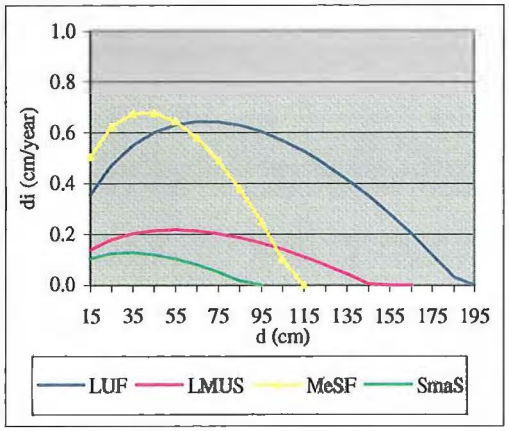


Figure 4.9b. unlogged plots

B. Linear model

Equation [8] as shown below was modified and fitted to each of these same four species group using standard regression procedures. Examination of the residuals from fitting the modified form of Equation [8] had suggested the need for square root transformation of the response variable d_i, as shown in Equation [8.a] below.

[8] $d_i = f$ (d, stand attributes in sub-plot level, locality factors)

[8.a] $\sqrt{d_i} = \beta_0 + \beta_1 d + \beta_2 \ln d + \beta_i$ (stand attributes) + β_j (locality factors)

Parameter estimates, and statistical measures to detect the degree of autocorrelation (Durbin-Watson statistic) and multicollinearity (largest condition index and variance inflation factor), obtained from fitting Equation [8.a] are presented in Table 4.23, while the complete output of the SAS runs are in diskette form (Appendix 4.13b). All variables in the equations were significant at least at the 5 % level ($p<0.05$), except for Group MeSF where the intercept was not significant even at the 10 % level.

Table 4.23. Parameter estimates, Durbin-Watson statistic (DW), largest condition index (COLLIN) and variance inflation factor (VIF), for 4 species groups obtained from fitting Equation [8.a]

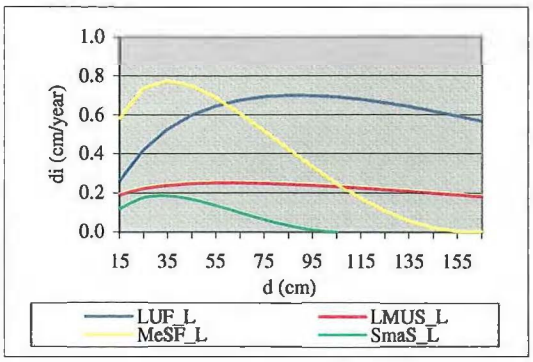
		SPECIES GROUPS			
		LUF	**LMUS**	**MeSF**	**SmaS**
PARAMETER ESTIMATES	β_0	-0.247188	0.188629	-0.329933^{NS}	-0.464108
	d	-0.003886	-0.001678	-0.012119	-0.011411
	Ln d	0.343233	0.100327	0.423835	0.367964
	tci	0	0.029741	0.160013	0
	ci*tci	-0.378985	0	0	0
	$G_{sp>d}$	0	0	0	-0.058570
	alt	-0.000337	-0.000164	0	0
	lov	0.105918	0.039906	0.092350	0.039968
RMS		0.1245	0.0469	0.1207	0.0318
DW		1.399	1.658	1.432	1.422
COLLIN		62.658	81.359	116.840	120.024
VIF		11.561	14.605	20.587	23.308
R^2 (adjusted)		0.12	0.05	0.06	0.04

NS : not significant; else, significant at least at α=0.05

Graphical inspection of growth pattern for each species group (Figures 4.10a-b) suggested that the larger tree species (Groups LUF and LMUS) reach maximum size much more slowly than the other two groups (MeSF and SmaS). Equation [8.a] also resulted in higher diameter increment prediction for all species groups and size classes, compared with the ones from the non-linear form, except for small diameter classes of Group LUF. This is evident when graphs of growth trends from both types of equation were overlaid (Figures 4.11a-b). Based on this observation, Equation [8.a] itself was modified through replacing variable Ln d with d^2 as shown in Equation [8.b] below, then re-fitted to each species group.

[8.b] $\sqrt{d_i} = \beta_0 + \beta_1 d + \beta_2 d^2 + \beta_i$ (stand attributes) + β_j (locality factors)

Final linear equations for the four species groups were selected by comparing statistical measures in Tables 4.23 to 4.24; as well as graphical plots of Appendices 4.13a-b and 4.14a-b, and growth trends (Figure 4.12a-b). Using these criteria (see section 3.3 of Chapter 3), Equation [8.b] was selected to be analysed further for comparison with corresponding non-linear equations.



PT. ITCI DATA

Figure 4.10a : from Equation [8.a]
Growth pattern for four species groups in **unlogged** plots, drawn using parameter values in Table 4.23; other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
alt=100 m a.s.l
Gsp>d=0.2 m^2/0.01 ha

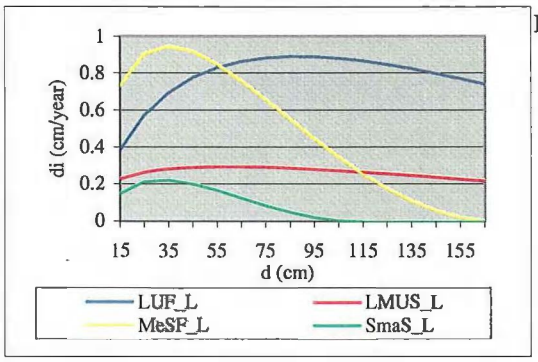


Figure 4.10b : from Equation [8.a]

Growth pattern for four species groups in **logged** plots, drawn using parameter values in Table 4.23; other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
alt=100 m a.s.l
Gsp>d=0.2 m^2/0.01 ha

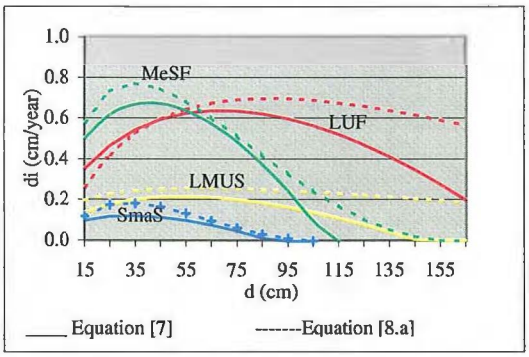


Figure 4.11a: from Equations [7] and [8.a]

Growth pattern for four species groups in **unlogged** plots, other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
alt=100 m a.s.l
Gsp>d=0.2 m^2/0.01 ha

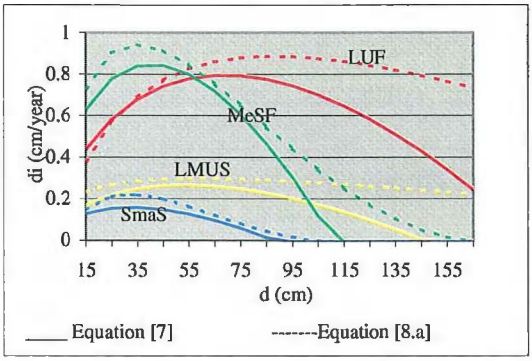


Figure 4.11b : from Equations [7] and [8.a]

Growth pattern for four species groups in **logged** plots, other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
alt=100 m a.s.l
Gsp>d=0.2 m^2/0.01 ha

Table 4.24. Statistical measures obtained through the univariate procedure for ($\sqrt{d}_{iact}$-$\sqrt{d}_{ipred}$), for Equations [8.a] and [8.b].

SPECIES GROUP	N	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LUF (1)	4273	0.279847	0.185502	-0.12177	1.734586
(2*)		0.279268	0.179757	-0.11073	1.736724
(2**)		0. 277714	0.161972	-0.15755	1.778657
LMUS (1)	8158	0.195917	0.391899	-0.33070	1.072397
(2*)		0.196009	0.392918	-0.33427	1.071962
(2***)		0.196443	0.395931	-0.34039	1.075194
MeSF (1)	1364	0.346964	0.210621	-0.48353	1.780364
(2*)		0.347093	0.214728	-0.47943	1.774413
(2***)		0.345298	0.190857	-0.47035	1.775716
SmaS (1)	1094	0.177904	0.469001	-0.28147	0.898198
(2)		0.177640	0.464849	-0.27610	0.906346

(1) : Equation [8.a]
(2) : Equation [8.b]; 2* : without variable SQ; 2** : with variable SQ; 2*** : variable lov replaced by SQ.

Figures 4.12a-b. Growth trends of four species groups, drawn from Equations [8.a] and [8.b]

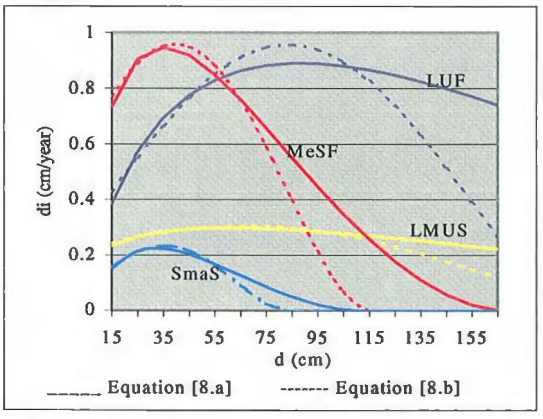


Figure 4.12a. logged plots.

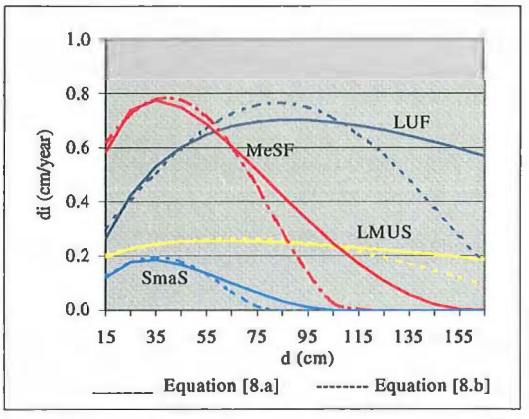


Figure 4.12b. unlogged plots

Table 4.25. Parameter estimates for each species group obtained from fitting Equation [8.b]

		SPECIES GROUPS						
		LUF		LMUS		MeSF		SmaS
		(*)	(**)	(*)	(***)	(*)	(***)	
PARAMETER ESTIMATES	β_0	0.505131	0.524149	0.404102	0.437494	0.493360	0.485582	0.196474
	d	0.011489	0.011674	0.002974	0.002996	0.013304	0.013736	0.014532
	d^2	-0.000068	-0.000070	-0.000022	-0.000022	-0.000168	-0.000170	-0.000204
	tci	0	0	0.031904	0.032703	0.161939	0.160309	0
	ci*tci	-0.379447	-0.368685	0	0	0	0	0
	$G_{sp>d}$	0	0	0	0	0	0	-0.058617
	alt	-0.000348	-0.000438	-0.000165	-0.000265	0	0	0
	lov	0.104404	0.033612	0.039661	0	0.092863	0	0.039960
	SQ	0	0.104771	0	0.012995	0	0.110652	0
RMS		0.07808	0.07723	0.03844	0.03861	0.12083	0.11958	0.03167
DW		1.395	1.411	1.655	1.648	1.431	1.446	1.422
COLLIN		18.259	18.715	20.372	19.944	31.184	30.745	20.747
VIF		13.797	13.819	13.503	13.510	21.843	21.831	20.374
R^2(adjusted)		0.13	0.14	0.05	0.04	0.06	0.07	0.04

(*) : without variable SQ; (**) : with variable SQ; (***) : variable lov replaced by SQ

For the purpose of comparison with the non-linear equations (Equations [7.a] to [7.d], the following linear equations were selected :

[8.b.1] $\sqrt{d}_{iLUF} = 0.505131 + 0.011489\,d - 0.000068\,d^2 - 0.379447\ ci*tci - 0.000348\ alt + 0.104404\ lov$

[8.b.2] $\sqrt{d}_{iLMUS} = 0.404102 + 0.002974\,d - 0.000022\,d^2 + 0.031904\ tci - 0.000165\ alt + 0.039661\ lov$

[8.b.3] $\sqrt{d}_{iMeSF} = 0.493360 + 0.013304\,d - 0.000168\,d^2 + 0.161939\ tci + 0.092863\ lov$

[8.b.4] $\sqrt{d}_{iSmaS} = 0.196474 + 0.014532\,d - 0.000204\,d^2 - 0.058617\ G_{sp}>d + 0.039960\ lov$

where :

d_{iLUF}.....d_{iSmaS} are mean annual diameter increments for each labelled species groups in cm/year; other variables are as stated in Chapter 3.

C. Comparison between non-linear Gompertz projection form and linear model

The best non-linear equations selected to represent each of the four species groups were compared with the best linear models. Before comparing the two functional forms, the model property for each form was evaluated using criteria stated in section 3.3 of Chapter 3.

The following are results of comparison between the two types of functional forms, obtained through the procedures explained in section 3.2.2 of Chapter 3.

Comparison in projection form (predicted d_2)

1. Mean residuals of predicted diameter (d_2) calculated over several actual interval lengths between measurements for both model types are presented in graphical form in Appendix 4.15. It can be seen from these figures that both model types under-predicted over short intervals (< 3 years), but non-linear ones had slightly higher mean residuals than linear models. For longer intervals, the non-linear models performed better; some were relatively unbiased, while others were much less biased than the linear form. This suggested some superiority of non-linear over linear models for longer-term prediction, which represents a major advance in scientific knowledge from a practical point of view,

2. Graphical plots of residuals and outputs of the SAS univariate procedure, obtained through expressing the fitted linear equations (d_i) in difference form (d_2) are included in Appendix 4.16a and in diskette form (Appendix 4.16b). The SAS univariate outputs, extracted from the full records in Appendices 4.9b (non-linear) and 4.16b (linear), are shown in Table 4.26.

Table 4.26. Statistical measures extracted from univariate outputs for (d_{2act}-d_{2pred}), derived from non-linear and linear equations.

SPECIES GROUP	FUNCT. FORM	N	MEAN RESIDUAL	SD (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LUF	LIN	4273	0.024886	1.003457	0.123448	1.558921	7.644517
	NON-LIN		0.127640	0.982887	0.309510	1.464404	6.971707
LMUS	LIN	8158	-0.01288	0.518471	-0.07042	1.582504	3.911359
	NON-LIN		0.095890	0.493047	0.396129	1.549175	3.455983
MeSF	LIN	1364	0.004582	1.415178	-0.01529	0.905786	10.38937
	NON-LIN		0.162605	1.388418	0.169003	0.829489	9.573077
SmaS	LIN	1094	-0.02246	0.428652	-0.39593	2.172356	3.133692
	NON-LIN		0.090719	0.396901	0.270055	1.511927	2.784865

Table 4.26 showed that the linear forms resulted in means of residuals closer to zero for all species groups and skewness also closer to zero except for Group SS, than the ones of non-linear form, but they had larger values of standard deviation (SD), kurtosis, and residual range. Moreover, graphical plots of both types of equation (Appendix 4.9a and 4.16a) exhibited less balance of residuals in the linear than in the non-linear forms. Hence, the overall results suggested that the non-linear form was preferable to the linear form.

Comparison in the form of diameter increment function (predicted d_i)

1. Graphical plots of residuals against average predicted d_i , obtained from both types of model showed positive skewed trends with about the same ranges (Appendix 4.17). This positive skewing of residuals patterns was also encountered when the response variable for the increment function was expressed in d_i (before transformation to $\sqrt{d_i}$),

2. Calculated mean residuals of predicted d_i over two (short and long) different ranges of actual interval by diameter class (Appendix 4.18), confirmed the earlier result when mean residuals over ranges of actual interval were calculated from predicted d_2. The non-linear form demonstrated its superiority over the linear form for the longer periods of prediction. For Groups LUF and LMUS in which most commercial species occur, relatively small mean residuals over most diameter classes were also practically advantageous.

3. Graphs depicting growth trends for each of the four species groups (Figures 4.13a- b), drawn from both non-linear (Equations [7.a-d] and linear (Equations [8.b.1-2]) equations, showed that the linear form resulted in larger maximum diameter increment than the non-linear form for all species groups. The value of d_i, for non-linear (projection) form was obtained by incrementing initial size (d) over one year intervals (t_2-t_1=1). Earlier results had indicated that both types of model under-predicted over short intervals with less bias for the linear than the ones of non-linear form. For long intervals, however, the non-linear performed better than the linear models (Appendices 4.15 and 4.18).

Figure 4.13a-b. Growth patterns of four final selected species groups for PT. ITCI data, drawn from non-linear (Equation [7.a-d]) and linear (Equation [8.b1-4]) models, assuming tci=0.8, ci=0.25 m^2/0.01 ha, alt=100 m a.s.l.

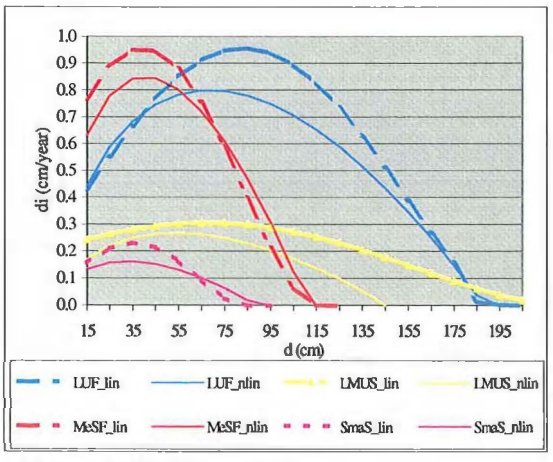


Figure 4.13a. logged plots.

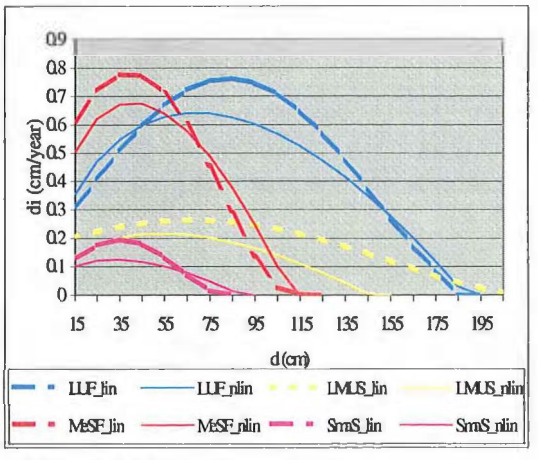


Figure 4.13b. unlogged plots.

4.1.2. Modelling PT. INHUTANI I data

Eight species groups were initially formed to model tree diameter growth of PT. INHUTANI I data. The groups consisted of : large, medium, small and other tree species, each of which was divided into faster and slower growing species (LF, LS, MF, MS, SF, SS, UF, US). The species groupings were tested, and the results and final selection of groups are presented in the next section.

Equation [7] modified with additional variables was fitted to each species group. Variables G_{sp}, ci, $G_{sp>d}$, tci, and lov, were stand attributes and locality factors incorporated in the modified form. Parameter estimates and residual mean squares (RMS) for each species group, as well as other statistical and graphical measures are presented in Tables 4.27 and 4.28, and in diskette form (Appendix 4.19a).

Results of fitting the modified Gompertz projection form showed a significant interaction effect between variables ci and tci for Group LF, which confirmed the finding in modelling the PT. ITCI data for Group LUF (combined group of LF and UF). Variable lov was the only additional term found to have a significant effect for the 5 groups, namely, LS, MF, MS, SF and SS. This variable was also found to be important for Groups LF and US, while Group UF exhibited no noticeable effect of additional terms included in the equation.

While other species groups exhibited the conformity between the estimate of α and observed maximum size (diameter), Group SF showed an anomaly. Group SF resulted in unrealistic estimates of the parameter α (Appendix 4.19a and Figures 4.14a-b) from both statistical and biological points of view. It can be seen in Appendix 4.19b, that the parameter α for Group SF had a much higher asymptotic standard error (0.6) than the corresponding ones for the rest of the groups, which vary from 0.02 to 0.06 cm. The asymptotic correlation matrix between parameter estimates was very high (min. 0.8), which might indicate over-parameterization. The Group SF, it should be remembered, had little representation (152 observations), and was dominated by the genus *Macaranga*, which is a short lived species, but one which grows much faster in gaps following logging activities. These are suspected to contribute to this anomaly. Omitting variable lov from the equation resulted in a smaller value of parameter α (Table 4.27), which reflected a growth trend biologically more acceptable in terms of maximum size commonly attained by species in Group SF, but with larger values of standard deviation, skewness (positive), kurtosis, and residual range (Table 4.28).

The effect of soil characteristic was examined by including this factor as a dummy variable, 1 for Uc3 soil category (SC = 1) and 0 (SC = 0) for other soil categories. It was found that variable SC did not much affect diameter growth for most species groups. The effect of this variable was noticeable only for Groups MS and US. While a slight improvement in the fit was obtained by including variable SC in the equation for Group US, Group MS showed otherwise, judged by the changes in its values of standard deviation, skewness, and kurtosis. The improvement for Group US, however, was negligible from a practical point of view because of only a very small improvement for the above measures, while the residual range showed a slight increase, and so this variable was dropped from the equations for Groups MS and US.

The possibility of aggregating species groups further was examined through graphical observation of Figures 4.14a-b and multiple comparison of the variance of predicted values (in the form of d_i), using Tukey's studentized range (HSD) test. The absolute values using this latter test have to be interpreted with caution, given the lack of independence in the data. Both the HSD test at alpha = 0.05 and Figures 4.14a-b confirmed the acceptability of combining medium, small, and other slower growing species (Groups MS, SS, US) into one group (Group MSUS). While the Tukey's studentized range (HSD) test showed the acceptability of consigning the Groups MF and SF into one group, Figures 4.14a-b did not fully confirm the result of this test. The difference between Groups MF and SF, however, was smaller than between MF and UF. This suggested that further aggregating Groups MF and SF might be more appropriate than MF and UF. As stated earlier, Group SF depicted an anomalous estimate of the parameter α when the variable lov was included in the equation. On the other hand, excluding the variable lov did not improve the model fit although a more realistic parameter value for α was obtained. Amalgamation of these two groups as Group MeSF, resulted in higher standard deviation, skewness, kurtosis, and residual range than for Group MF or SF alone (Table 4.28). At this stage, the choice is between aggregating the Groups MF and SF into one group (MeSF) so that the anomaly could be eliminated (Table 4.27 and Figures 4.15a-b), or excluding Group SF from the analysis since its representation is negligible.

Five species groups of LF, LS, MeSF, MSUS, and UF, were finally selected to express diameter growth for PT. INHUTANI I data. Parameter estimates and residual mean square (RMS) values for the 5 selected species groups are presented in Table 4.27. Other statistical and graphical measures are in Table 4.28; Figures 4.15a-b and Appendices 4.19a. Equations [7.e] to [7.i] are the functional forms for each selected species group. Residual

patterns for these equations, however, showed clear positive skewness except for Group MeSF (Appendix 4.19b). The implications of this outcome could be the need for identifying other functional forms and/or more data from longer periods of measurement being required to fit this functional form, as explained more in detail in the discussion section.

[7.e] $$d_{2LF} = \text{Exp}\,(\text{Ln}\,(d_1).e^{-(0.00994 + 0.00326.lov - 0.01078.ci*tci)\,(t2-t1)} + 5.08038(1-e^{-(0.00994 + 0.00326.lov - 0.01078.ci*tci)\,(t2-t1)}))$$

[7.f] $$d_{2LS} = \text{Exp}\,(\text{Ln}\,(d_1).e^{-(0.00698+0.00300.lov)\,(t2-t1)} + 4.78343\,(1-e^{-(0.00698+0.00300.lov)\,(t2-t1)}))$$

[7.g] $$d_{2MeSF} = \text{Exp}\,(\text{Ln}\,(d_1).e^{-(0.01163 + 0.00993.lov)\,(t2-t1)} + 4.44803(1-e^{-(0.01163 + 0.00993.lov)\,(t2-t1)}))$$

[7.h] $$d_{2MSUS} = \text{Exp}\,(\text{Ln}\,(d_1).e^{-(0.00701 + 0.00352.lov - 0.00183.ci - 0.00702.ci*tci)\,(t2-t1)} + 4.67692\,(1-e^{-(0.00701 + 0.00352.lov - 0.00183.ci - 0.00702.ci*tci)\,(t2-t1)}))$$

[7.i] $$d_{2UF} = \text{Exp}(\text{Ln}\,(d_1).e^{-0.01671(t2-t1)} + 4.57341\,(1-e^{-0.01671(t2-t1)}))$$

where :

d_{2LF}.....d_{2UF} are tree diameters in cm at time 2 for species groups; other variables are as stated in Chapter 3.

Table 4.27. Parameter estimates and residual mean squares (RMS), obtained from fitting the modified form of Equation [7] to PT. INHUTANI I data.

SPECIES GROUP	N	PARAMETER ESTIMATES					RMS
		α	β_0	β_1 (lov)	β_2 (ci)	β_3 (ci*tci)	
LF*	4310	5.080380530	0.009939741	0.003261004	0	-0.010780451	0.5640
LS*	6084	4.783434399	0.006983619	0.003004384	0	0	0.2748
MF	376	4.452169720	0.013571242	0.007339652	0	0	0.3468
MS	2828	4.568322767	0.006240501	0.004704801	0	0	0.2008
SF	152	5.264260348	0.005284706	0.008257055	0	0	0.2966
		4.303941667	0.017034374	0	0	0	0.42121
SS	1909	4.647270099	0.005983661	0.003842504	0	0	0.1750
UF*	984	4.573405097	0.016712125	0	0	0	0.4454
US	12240	4.669622428	0.007197762	0.003327498	-0.001973377	-0.006944188	0.2138
MeSF*	530	4.448034513	0.011625597	0.009932233	0	0	0.3554
MSUS*	16977	4.676921154	0.007007396	0.003520644	-0.001834100	-0.007015286	0.2070

Note : all variables were significant at 95 % confidence interval.

Table 4.28. Statistical measures for residuals (d_{2act}-d_{2pred}), obtained through SAS univariate procedure of fitting the modified form of Equation [7] to PT. INHUTANI I data.

SPECIES GROUP	N	MEAN	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF*	4310	-0.00011	0.750941	0.95965	1.172768	4.752886
LS*	6084	0.002063	0.524086	1.143601	1.610736	3.239474
MF	376	-0.00636	0.587315	0.536585	0.271644	3.499503
MS	2828	-0.00278	0.447889	1.114587	1.425824	2.566347
SF	152	-0.00680	0.540909	0.621978	0.664505	2.89779
		-0.00388	0.646839	1.082937	1.055167	3.050807
SS	1909	-0.00797	0.418094	1.168275	1.551735	2.41769
UF*	984	-0.01035	0.666969	0.687571	0.188341	3.667667
US	12240	-0.00374	0.462261	1.183922	1.664909	2.812335
MeSF*	530	-0.00738	0.594943	0.686812	0.699755	3.971540
MSUS*	16977	-0.00434	0.454575	1.174298	1.641132	2.816482

* : Final selected species group

PT. INHUTANI I DATA

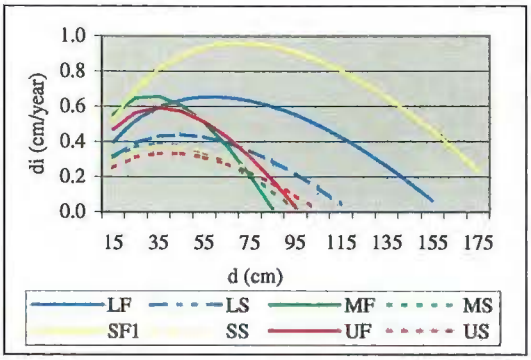


Figure 4.14a
Growth pattern for 8 species groups in logged plots, drawn using parameter estimates in Table 4.27; other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
G>d=0.2 m^2/0.01 ha

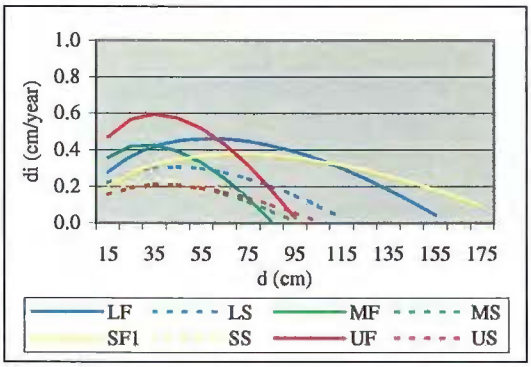


Figure 4.14b
Growth pattern for 8 species groups in unlogged plots, drawn using parameter estimates in Table 4.27; other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
G>d=0.2 m^2/0.01 ha

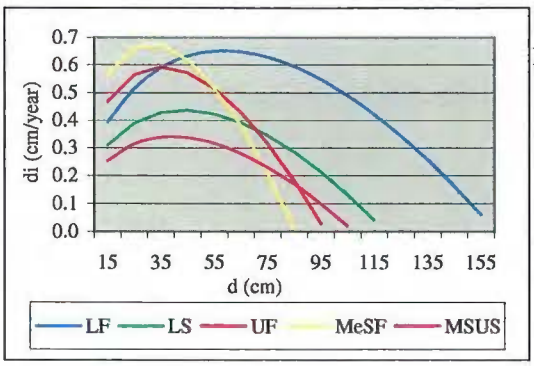


Figure 4.15a
Growth pattern for 5 species groups in logged plots, drawn from Equations [7.a] to [7.I], other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
G>d=0.2 m^2/0.01 ha

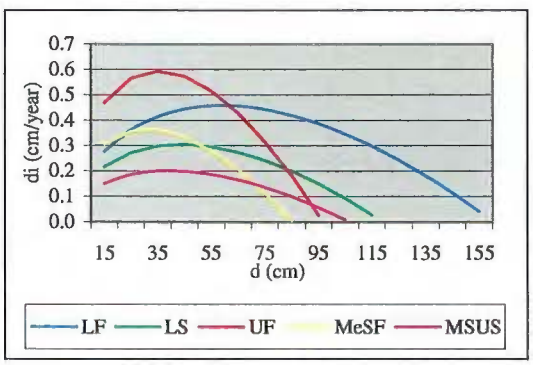


Figure 4.15b
Growth pattern for 5 species groups in unlogged plots, drawn from Equations [7.a] to [7.I], other variables are held constant, for example :
tci=0.8
ci=0.25 m^2/0.01 ha
G>d=0.2 m^2/0.01 ha

4.1.3. Modelling combined PT. ITCI/PT. INHUTANI I data

Combined PT. ITCI and PT. INHUTANI I data comprised 1013 species, where some 110 species existed in both localities. Among the 110 species which occurred in both locations, 97 species fell into the same groups when using faster and slower growing criteria. For the remaining 13 species which fell into different groups (faster or slower growing species), 9 species in the PT. ITCI data had too little representation to be tested; 2 species in the PT. ITCI data did not show clear bias when the chosen model was fitted to these species; and 2 other species had too few representation in both locations. The thirteen species were then included in either other faster or slower growing species, using the same criteria as for grouping other species (average d_i per 1 cm diameter class)

For the purpose of modelling the combined PT. ITCI/PT. INHUTANI I data, as explained in section 3.2.1 of Chapter 3, the following three different ways of aggregating species were examined.

- Aggregations of species into four species groups, namely: faster and slower growing Dipterocarp species (DF, DS); faster and slower growing non-Dipterocarp species (NF, NS);
- Aggregations of species into eight species groups of large, medium, small, and other faster growing species (LF, MF, SF, UF); and large, medium, small, and other slower growing species (LS, MS, SS, US);
- Aggregations of species into ten species groups of : LF, LS, MF, MS, SF, SS, DF, DS, NF, and NS.

A modified form of the Gompertz projection equation (Equation [7]), incorporating stand attributes and locality factors (G_{sp}, ci, G_{sp}>d, tci, lov, and loc) was fitted to each species group in the three aggregation. The results for each grouping are presented in the next section.

A. Four species groups

Results of fitting the Gompertz projection form (modified from Equation [7]) to the four species groups are summarized in Tables 4.29 and 4.30. They consist of parameter estimates and residual mean square (RMS) values; and other statistical measures for residuals extracted from the SAS univariate output; while graphical measure of residual distributions and the complete SAS outputs for the 4 groups are presented in Appendices 4.20a-b.

The existence of a combined effect of above and below ground competition was found in three groups (DF, DS, NS), shown by the substantial effect of interaction between the variables ci and tci (ci*tci).

Table 4.29. Parameter estimates and residual mean squares, obtained from fitting the modified form of Equation [7] to 4 species groups for the combined data.

SPECIES GROUP		DF	DS	NF	NS
df		6818	5573	3691	23683
PARAMETER ESTIMATES	α	5.145806414	4.984046548	4.826741064	4.770460780
	β_0	0.007912022	0.006568828	0.007817423	0.005837697
	β_1 (tci)	0.001840475	0	0.003631350	0.000824675
	β_2 (lov)	0.003606979	0.002675334	0.004523997	0.002375325
	β_3 (ci*tci)	-0.007447256	-0.005751220	0	-0.003333619
	β_4 (loc)	0	-0.001913242	0.001345764	-0.002335140
RMS		0.7520	0.2289	1.0630	0.1960

The results of including a dummy variable loc (localities), 1 for PT. ITCI and 0 for PT. INHUTANI I in the equation, did not show a noticeable effect on predicted d2 for faster growing Dipterocarp species (Group DF), but did for the other three.

A graphical measure of the distribution of residuals (Appendices 4.20a-b) did not clearly show any skewed residuals for faster growing species (Groups DF and NF), while the two other groups (DS and NS) indicated a slight positive skewness. This can also be seen from Table 4.30 where the faster growing species (Groups DF and NF) had smaller skewness than for the slower growing species (DS and NS).

Table 4.30. Statistical measures for residuals, obtained through SAS univariate procedure of fitting the modified form of Equation [7] for 4 species groups for the combined data set.

SPECIES GROUP	N	MEAN RESIDUAL	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
DF	6818	0.063659	0.86465	0.578775	1.669025	6.80158
DS	5573	0.009729	0.478131	0.831415	0.993676	3.475577
NF	3691	0.120846	1.023355	0.363352	1.142734	7.680504
NS	23683	0.030883	0.441219	0.773870	0.950130	3.720011

B. Eight species groups

This section presents the results of fitting the Gompertz projection form (modified from Equation [7]) to the eight species groups. Parameter estimates, residual mean square (RMS) values, and other statistical measures extracted from the SAS univariate output, are presented in Tables 4.31 and 4.32 respectively. Residual plots and the complete SAS outputs for the 8 species groups are included in Appendices 4.21a-b.

The existence of a combined effect of above and below ground competition, demonstrated by the important effect of interaction between the variables ci and tci (ci*tci) was found in three Groups of LF, MS, and US. The variable tci, without ci*tci in the model, was also found to have an important effect for three faster growing species groups (LF, MF and UF) and two slower growing species groups (MS and US).

Accumulated basal area of trees larger than the subject tree within a sub-plot seems to be an important competition factor affecting diameter growth of small slower growing species (Group SS).

The inclusion of the dummy variable loc (localities), 1 for PT. ITCI and 0 for PT. INHUTANI I, in the equation, showed a substantial effect on predicted d_2 values for most species groups except the Groups LF and UF. Localities seem to affect diameter growth of Group SF more strongly than the variable lov, as shown through the small effect of including the variable lov.

Residual plots for the eight species groups (Appendices 4.21a-b) exhibited consistency in residual distributions between faster and slower growing species. Residuals of the faster growing groups were not clearly skewed, while conversely, the slower growing group showed clear skewness in a positive direction. It can also be seen in Table 4.32 that the faster growing groups were found to have smaller skewness values than the slower growing ones.

Table 4.31. Parameter estimates and residual mean squares (RMS), obtained from fitting the modified form of Equation [7] to 8 species groups for the combined data set.

SPECIES GROUP	N	PARAMETER ESTIMATES							RMS
		α	β_0	β_1 (tci)	β_2 (G_{sp}>d)	β_3 (lov)	β_4 (ci*tci)	β_5 (loc)	
LF	6691	5.158755832	0.007424849	0.002057976	0	0.003361113	-0.005803927	0	0.7750
LS	8163	4.799821585	0.007242189	0	0	0.002056480	0	-0.003112658	0.2250
MF	1411	4.644974762	0.010926852	0.004919667	0	0.004621594	0	0.002371149	1.4648
MS	4705	5.003539031	0.005244375	0.000657399	0	0.002257927	-0.005415637	-0.001808612	0.2060
SF	333	4.351140577	0.016340952	0	0	0	0	0.006822828	0.8365
SS	2802	4.669081877	0.006958550	0	-0.001939525	0.002153288	0	-0.003118014	0.1626
UF	2095	4.767909312	0.008688089	0.003552652	0	0.004528283	0	0	0.7657
US	13591	4.787016345	0.005563898	0.000979338	0	0.002795019	-0.005213572	-0.002281195	0.1970

Note : all variables were significant at 95 % confidence interval.

Table 4.32. Statistical measures for residuals, obtained through SAS univariate procedure of fitting the modified form of Equation [7] to 8 species groups for the combined data set.

SPECIES GROUP	N	MEAN RESIDUAL	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF	6691	0.064727	0.877567	0.570581	1.613296	6.83252
LS	8163	0.030092	0.473273	0.733601	0.888094	3.415918
MF	1411	0.13362	1.20117	0.088856	0.776025	8.463644
MS	4705	0.039011	0.451907	0.689643	1.12237	3.39876
SF	333	0.035918	0.911113	0.540675	0.142975	4.692282
SS	2802	0.026744	0.402014	0.833671	1.224021	2.906628
UF	2095	0.092457	0.869495	0.590716	1.828456	6.880173
US	13591	0.021763	0.442783	0.837141	0.927792	3.328524

C. Ten species groups

The same equation used for the sets of four and eight species groups, was fitted to the 10 species groups (Equation [7]). Parameter estimates and residual means square (RMS) values, obtained from fitting the modified form of Equation [7] to the ten species groups are presented in Table 4.33; while other statistical and graphical measures are in Table 4.34, and Appendices 4.22a-b.

A measure of tree dominance/tree competition index (tci) was found important for faster growing species except for Group SF. Its interaction with variable ci was also found to have significant effect for some faster and slower growing species, which indicated the existence of a combined effect of above and below ground competition.

Accumulated basal area of trees larger than the subject trees in sub-plots proved to be an important competition factor affecting diameter growth of small slower growing species (Group SS), which confirmed the earlier finding in PT. ITCI data and for the 8 species groups.

Dummy variable loc (localities) 1 for PT. ITCI and 0 for PT. INHUTANI exhibited a substantial effect on predicted d2 for most species groups except LF, DS and NF. Similar to earlier findings, localities (variable loc) seemed to be affecting diameter growth of Group SF group more strongly than variable lov, as depicted by the substantial and trivial effects of the variables loc and lov respectively

Graphical inspection of residual pattern for the ten groups (Appendices 4.22a-b) displayed a slight skewing of residuals for Groups DF and LS, least skewed for the other four faster growing groups, and clearly skewed for the rest of slower growing species groups. While the other 8 groups showed consistency of residual patterns and distributions between faster and slower growing species groups, the Groups DF and LS showed otherwise. It should be noted that the Group DF comprised a bigger proportion of PT. INHUTANI I than PT. ITCI data; while Group LS comprised a smaller proportion of PT. INHUTANI I than PT. ITCI data (see Appendix 3.11).

Table 4.33. Parameter estimates and residual mean squares (RMS), obtained from fitting the modified form of Equation [7] to 10 species groups for the combined data set.

SPECIES GROUP	N	PARAMETER ESTIMATES							RMS
		α	β_0	β_1 (tci)	β_2 (G_{sp}>d)	β_3 (lov)	β_4 (ci*tci)	β_5 (loc)	
LF	4437	5.196900298	0.006897259	0.002188049	0	0.003744845	-0.004908589	0	0.782
LS	3678	4.759911235	0.006705930	0	0	0.001579119	0	-0.002404336	0.2048
MF	510	4.520334062	0.018570585	0.012165914	0	0.006906975	0	-0.007741484	2.4849
MS	2320	4.780915341	0.005919706	0.000988586	0	0.003257242	-0.010664225	-0.002317449	0.2111
SF	279	5.248253313	0.010081484	0	0	0	-0.023140602	0.005431490	0.8602
SS	912	4.598458078	0.007474536	0	-0.003521779	0.002619372	0	-0.003473057	0.1656
DF*	2821	5.080642186	0.008681621	0.001196758	0	0.003619866	-0.011258314	0.000629477	0.6960
DS*	4170	5.049119203	0.006266491	0	0	0.002401343	-0.005184050	0	0.2523
NF*	2486	4.802137583	0.009306884	0.003992282	0	0.004781915	0	0	1.1998
NS*	17576	4.838338045	0.005618752	0.000918420	0	0.002264372	-0.005048059	-0.002174862	0.188

Note : 1) all variables were significant at 95 % confidence interval; 2) * : groups for species existing only either in PT. ITCI or PT. INHUTANI I data.

Table 4.34. Statistical measures for residuals , obtained through SAS univariate procedure of fitting the modified form of Equation [7] to 10 species groups for the combined data set.

SPECIES GROUP	N	MEAN RESIDUAL	STANDARD DEVIATION (cm)	SKEWNESS	KURTOSIS	RESIDUAL RANGE (cm)
LF	4437	0.073513	0.880798	0.552109	1.778066	6.915017
LS	3678	0.046365	0.449953	0.654592	0.870885	2.956744
MF	510	0.156216	1.562353	0.395599	1.851987	10.83723
MS	2320	0.029425	0.458014	0.803183	1.625668	3.487816
SF	279	0.019843	0.922222	0.411418	-0.14424	4.505745
SS	912	0.022861	0.405413	0.921114	1.522497	2.817226
DF*	2821	0.03700	0.832681	0.679053	1.934033	6.725118
DS*	4170	0.005662	0.502056	0.926591	1.607421	4.183345
NF*	2486	0.124427	1.087601	0.386882	1.445241	8.009914
NS*	17576	0.028158	0.432693	0.748415	0.771013	3.138333

4.2. DISCUSSION

4.2.1. Species grouping

The purpose for building a model is an important factor to be considered when selecting ways of species grouping for modelling growth of mixed species. Ideally, researchers should use criteria for species grouping which appropriately reflect the intended use of the model, as well as growth characteristics of the species to be aggregated. However, available information and limited knowledge regarding individual species characteristics and their interaction with other species in a forest seem to preclude the use of these two criteria jointly in modelling tropical rain forests, particularly rain forest of Kalimantan which has a high species richness but is dominated by one family only (*Dipterocarpaceae*).

Some research publications on modelling mixed species reported numerical (statistical) analyses in aggregating species, but subjective approaches were involved in reaching the final groupings, of which the resulting groups may also be data or functional form dependent, e.g . Meldahl *et al.* (1985), Leach *et al.* (1991), Vanclay (1991b), and Alder (1995).

Species grouping used in growth studies for dipterocarp forests separated species on the basis of dipterocarps and non-dipterocarps, and/or between commercials and non-commercials: for example, Wan Razali (1988, 1989), Suhendang *et al.*(1995), Nguyen-The (1996), and Pambudhi (1997). The tendency to separate dipterocarps from non-dipterocarps or between commercial and non-commercial species may be suitable for the intended use of the model, but the great variability in growth rates among species of dipterocarps, as stated in section 2.2.1 of Chapter 2, may be overlooked by so doing.

It is not always easy to justify which way to group species is best, since the difficulties stated earlier and intentions of researchers in building models, would likely affect the criteria used for grouping species. Moreover, many species of tropical rain forests have only very little representation, and so limit the possibility of examining the adequacy of fit of a model for a number of individual species in a group. Vanclay (1994b) pointed out that grouping species based on maximum attainable size may not provide a good indication of growth responses critical in modelling. Thus, growth rates alone may result in unsatisfactory grouping, since growth rates will vary even within species due to size, site quality,

competition, as well as genetic factors. However, in many cases of tropical rain forests, data for a large number of species do not cover wide ranges of size, information on site quality may not always be available, adjusting growth rates with level of competition will be impractical, and genetic factors for many tropical species are little known as yet.

It was found in this study that empirical grouping using maximum attainable size based on published and observed data, local knowledge, and growth rates, with continual examination during the process of modelling, offered a useful way for aggregating species of PT. ITCI data into four species groups (LUF, LMUS, MeSF, and SmaS). The reasons were: firstly, information regarding maximum attainable size for 67 % of a total 491 species was available. The remaining species, maximum attainable size for which were not known, were mostly identified either up to the level of family or genus only, or occurred with little representation. Secondly, in trying to minimize the problem using maximum attainable size and average growth rates for species grouping, further re-aggregation of species groups based on maximum attainable size to faster and slower growing species was done using average diameter increment per 1 cm diameter class, and then re-evaluated during the process of modelling. Plotting the selected models for the four groups of PT. ITCI to individual species with many data also suggested the soundness of PT. ITCI species grouping (see Appendix 4.10).

Grouping species into faster and slower growing species can sometimes be data specific, but this was not so in the study reported here. Experience in grouping PT. ITCI and PT. INHUTANI I data resulted in 97 out of 110 species which existed in both localities falling into the same groups when the faster and slower growing criteria were used. For 13 species which fell into different groups (faster or slower growing species), 9 species in the PT. ITCI data had too little representation to be tested, 2 species in the PT. ITCI data did not exhibit bias when the chosen model was fitted to these species, and 2 other species had too few observations in both localities. The finding from grouping species of the PT. ITCI and the combined PT. ITCI/PT. INHUTANI I data indicated that species aggregation using the criterion maximum attainable size, based on published and observed data, local knowledge, and average growth rate per 1 cm diameter class, was appropriate particularly for individual species which cover wide ranges of diameter. The implication of this finding for future research is the need to concentrate firstly on species with adequate representation when using these criteria for grouping species; and then determine whether species with less representation need to be aggregated as separate groups or can be combined with the most

similar existing groups, depending upon the importance of each species from a management point of view.

4.2.2. Growth models examined and final models selected

4.2.2.1. PT. ITCI data

A. Equations [1] and [2]

Comparison of statistical measures in Tables 4.2, 4.4, and 4.5, as well as the effect of initial size (d, ln d, d^2) (Tables 4.1 and 4.3) indicated that neither equation [1] nor [2] showed clear superiority in expressing diameter increment for most species groups, except for Groups SF and US, which were better expressed with Equation [1]. Since both equations required negative signs for the variables d^2 in Equation [1] and d in Equation [2] to conform to tree growth concepts, the continuous increase of resulting growth trends (Figures 4.1 and 4.2) for the medium slower growing species groups (Group MS) was deemed untenable. The other faster growing species (Group UF) showed similar trends to Group MS as a result of the very small value of coefficients for the variables d^2 (Equation [1]) and d (Equation [2]).

Despite the deficiencies of the models in terms of the effect of each variable in Equations (Table 4.1 and 4.3), skewed residuals and/or multicollinearity problems for some species groups, especially Equation [2], consistent effects of soil characteristics and altitude (SQ, alt) were evident. These two variables seem to be group dependent. Consistency of explanatory variables in both equations was also demonstrated by small tree species, where no additional term was found to be important for Group SF; and there appeared to be consistent combinations between the variables $G_{>d}$/ln (d+1) and lov for Group SS.

Growth trends obtained from Equation [1] (d_i as a function of initial diameter and its square) suggested that tree growth ceased earlier than for the one obtained from Equation [2](d_i as a function of initial diameter and its logarithm), except for the Groups MS and UF which appeared to provide anomalous results. Similar growth trends were found by Vanclay (1994b) when he compared his 1991b model to Wykoff's (1990) model.

B. Equation [3]

Despite differences in model forms, results similar to Equations [1] and [2] were found in Equation [3]: clear negative skewing of residuals for Groups LF and MF; a negative

sign for skewness for all species groups; and consistency of variables SQ and alt, which reflected group more than model form dependency. Other variables such as G, $G_{>d}$, $G_{>d}/\ln(d+1)$, and lov may be influenced by model forms and/or combinations of explanatory variables. The different effects of the first three variables (G, $G_{>d}$, $G_{>d}/\ln(d+1)$) in Equations [1] to [3] might also result from a multicollinearity problem, particularly for Equation [2] (see Table 4.5).

The variable lov was probably confounded with variables SQ and geom, since most logged plots were located in better soils, and in the same category of geomorphology for all logged plots (see Table 3.1 of Chapter 3).

In terms of the importance of each explanatory variable in affecting the response variables, Equation [3] was found to be preferable for expressing diameter growth for the eight species groups over Equations [1] and [2]. In addition, Equation [3] did not exhibit skewed residuals except for Groups LF and MF. This equation also imposed a maximum size (d_{max}), which prevented the occurrence of continuous increase in diameter growth (see Figure 4.3). This equation, however, has a limitation as explained in section 3.2.2 of Chapter 3, namely the difficulty in determining d_{max} for the type of forest under study.

C. Equations [4] to [6]

A modified beta function (Equation [5]) was found to be preferable to the other two functional forms used (Equations [4] and [6]) in terms of the significance of each explanatory variable in affecting the response variable (see Tables 4.8, 4.11, and 4.14). Diameter increment of medium tree species (Group M) proved to be difficult to model using $\ln d_i$ as a response variable, shown by the same results from fitting Equations [1], [2], and [4]. A multicollinearity problem was evident for Equation [4], and a non-significant effect of variable d for Group M was found when fitting Equation [6].

Larger residual ranges were obtained from fitting the linear (empirical) model and modified beta functions to the four groups of L, M, S, and U, than for the eight species groups. This could be an indication of the need for dis-aggregation of the four species groups. Clear evidence of multicollinearity for Equation [4] and limitations of Equations [4] and [6], could also be an indication of the need for exploring other functional forms, such as sigmoid functions which have been widely used for modelling even-aged stands.

D. Equation [7] for 8 species groups and all species/groups as dummy variables

Fitting Equation [7] to 8 species groups separately and putting the 8 groups as dummy variables as described in section 4.1.1.3, was aimed at identifying the best possible model to express diameter growth for this particular forest, and at exploring further the most suitable species grouping. The outcome from fitting Equation [7] in this way was used as a guide to decide: a). whether one model for all species, but allowing each species group to have different α values (which reflect maximum size), could express tree diameter growth appropriately or that it could be better represented by a separate model for each of the eight species groups, judged by criteria explained later in this section; and b). whether further aggregation of the eight species groups was necessary and a similar degree of model quality could still be obtained when the species groups were further aggregated into a smaller numbers of groups.

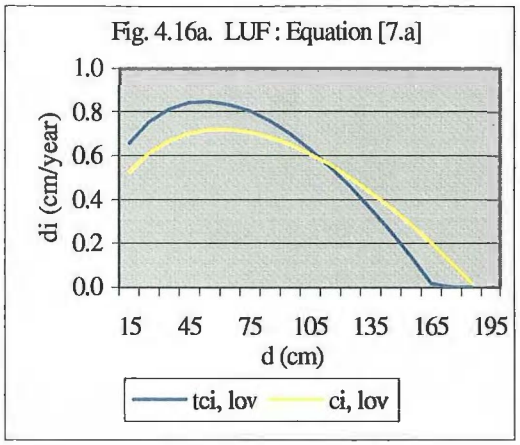
Examination of residual ranges for each species group (Table 4.17), and graphical inspection of residuals (Appendix 4.6a) and growth trends (Figure 4.7) indicated the possibility of re-aggregating 8 species groups into smaller groups. Using one equation for all species and putting the 8 groups as dummy variables (Equation [7.2]), demonstrated poorer fits than using separate equations for each species group in terms of residual ranges, departure from normality assumptions, and from logical and biological considerations. Equation [7.2] resulted in a larger residual range than for the eight species groups, quite a number of observations had random normal deviates (RND) greater than 3.5, and a large value of kurtosis (5.46); indicated the need for further examination of the model. Excessive values of the parameter α for Groups MF and SF, were not tenable from biological points of view (see Figure 4.8). These findings suggested the importance of developing separate models for each species group, and for this purpose, species aggregation into a manageable number of species groups with the least possible loss of precision, by reducing the numbers of species groups, was crucial. For this reason, further aggregation of 8 species groups to a smaller number of species groups was then considered. This re-aggregation was done firstly through multiple comparison of the average observed diameter increment per 1 cm diameter class (Tukey's test) for the eight species groups. This analysis resulted in the formation of four species groups, LUF, LMUS, MeSF, and SmaS. The appropriateness of this grouping was further examined as explained in the next section.

E. Equation [7] for Groups LUF, LMUS, MeSF, and SmaS

The Gompertz projection form, which incorporated stand attributes and locality factors was found to have unbiased residual patterns and distributions when fitted to the four species groups of LUF, LMUS, MeSF, and SmaS. Comparison of the changes in residual patterns and distributions, the values of skewness, kurtosis, residual ranges, and growth trends of selected species groups with the earlier grouping (8 species groups); as well as fitting the chosen model for each species group to individual species with many data confirmed the soundness of this particular grouping.

A measure of tree dominance (tci) clearly represented the competition effect better than accumulated basal area excluding the subject tree (ci) in the absence of variable alt for Group LUF. This was evident when comparing the RMS values (Table 4.19), and other statistical and graphical measures (Table 4.20 and Appendix 4.8). A possible explanation of this result is because the variable ci (G_{sp}-g) implied one-sided only competition, and so this put high weight of competition on to trees of smaller size (smaller diameter); on the other hand, variable tci (1-($G_{sp>d}$)/G_{sp}) implied two-sided competition, and that put high weight of competition on to trees of large size when tree growth started slowing down (see Figure 4.16a). The difference in the effect of the two variables (ci and tci) became unclear when variable alt was included in the equations. It was probably caused by a joint effect of variables ci and alt, as well as tci and alt; where both variables ci and tci had the same effect (see Figure 4.16b). When both variables alt and ci*tci were in the equations, the combination between tci and other variables was found to give a better fit than one between ci and other variables (see Table 4.20, Appendix 4.8).

A measure of tree dominance (tci) seemed to be a better variable to express competition for faster growing species groups than other variables examined, shown by better performance of equations consisting of variables tci than ci for Group LUF, and variables tci than $G_{sp>d}$ for Group MeSF. Explanation of this outcome is, perhaps, because these two groups were dominated by low light intolerant species. Thus, a measure of tree dominance in a stand (1-$G_{sp>d}$/G_{sp}) had a stronger effect on diameter growth than basal area of surrounding trees for Group LUF or basal area of trees larger than the subject tree for Group MeSF. Also because the variable tci reflected two sided competitions, it too indicated that both competitions for light and below ground resources were important factors affecting diameter growth than below ground competition only (variable ci) for Group LUF or above ground competition only (variable $G_{sp>d}$) for Group MeSF.



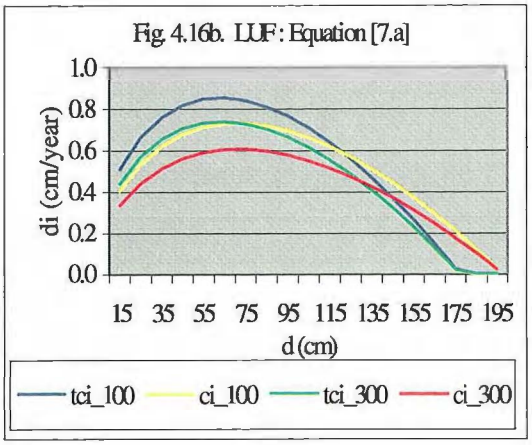


Figure 4.16a. Different growth pattern shown by Group LUF, obtained from Equation [7.a] with 2 different combinations of additional terms (ci with lov and tci with lov).

Figure 4.16b. Different growth pattern shown by Group LUF, obtained from Equation [7.a] with 2 different combinations of additional terms (ci with lov and alt; and tci with lov and alt).

Variable G_{sp}>d was evidently an important competition factor for Group SmaS. Since this group comprised many species but with little representation, it was quite difficult to relate this effect to species characteristics. It was probably related, however, to crown size and exposure. Individual trees with bigger crowns and better exposure will grow faster than the ones (from the same species) with smaller crown and shaded by other trees. Dawkins (1963b), for example, suggested the existence of a linear relationship between crown diameter and bole diameter. Accordingly, bigger trees from the same species have bigger crowns. Variable $G_{sp>d}$ has been used widely as a measure of competition for light. Group SmaS consisted of typical understorey species, and so the availability of light depends very much on trees which over-shade them. For this group, the bigger the tree in a sub-plot, the smaller is the value of $G_{sp>d}$, and the smaller the variable $G_{sp>d}$ the greater the diameter growth. Furthermore, $G_{sp>d}$ was the only competition factor found to have a significant effect for Group SmaS. This finding suggested that competition for light was the only detectable limiting factor affecting diameter growth of small slower growing species for this particular forest.

F. Equations [8.a] and [8.b] for Groups LUF, LMUS, MeSF, and SmaS

Results from fitting linear models (equations [8.a] and [8.b]) showed that a square root transformation of the response variable was the most appropriate transformation to stabilize non-homogenous variance of individual tree diameter increment models for PT. ITCI data.

Examination of Equations [8.a] and [8.b] showed that both equations had similar patterns of residuals (Appendices 4.13a and 4.14a). Furthermore, within the ranges of data used to fit the models, both equations showed the same growth path except for larger trees of faster growing species groups (Figures 4.12a-b). Equation [8.b] for the four species groups of LUF, LMUS, MeSF, and SmaS, however, was selected to be compared with the non-linear models (Equation [7]) for the same species groups, for the reasons set out below.

Equation [8.b] was clearly better than Equation [8.a] to model diameter increment of Groups LUF and SmaS, judged mainly using statistical measures presented in the results section. For Groups LMUS and MeSF, Equation [8.b] did not prove to be superior over Equation [8.a] when judged using the statistical measures in Table 4.24 only. Equation [8.b], nevertheless, was chosen to express tree diameter increment for the Group LMUS and MeSF, since this equation provided more reasonable extrapolation beyond the ranges of the available data. Until the data to test this assumption become available, it was considered safer to use Equation [8.b] rather than [8.a].

G. Summary of results from modelling PT. ITCI data

The Gompertz projection form, which incorporated stand attributes and locality factors was found to provide the best fit among functional forms examined for the PT. ITCI data. This form of equation resulted in reasonable residual patterns and distributions for the four selected species groups (LUF, LMUS, MeSF, SmaS). Comparison of this equation with the best linear model for the same data, suggested the superiority of this function over the best linear one, as set out below :

- The Gompertz projection forms performed better than the linear models for longer periods of prediction and over a wide range of diameters; this was judged based on the values of mean residuals of predicted future diameter (d_2), and the values of mean residuals of predicted diameter increment (d_i) per 10 cm diameter class respectively (see Appendices 4.13a and 4.15). Moreover, the values of mean residuals for predicted d_i in the larger tree species groups (Groups LUF and LMUS) were relatively small over most diameter classes. These findings represent a major practical advance in scientific knowledge, because : 1) the potential of the models to be used for longer prediction periods would reduce costs for inventory activities in the long term; and 2) the relatively small values of mean residual over most diameter classes for Groups LUF and LMUS were practically advantageous since most commercial species fell in these two groups.

- The Gompertz projection forms resulted in better residual distributions of predicted future diameter (d_2) than linear models (see Appendices 4.9a and 4.14a).

Among additional terms examined, variable lov seemed to be an important variable for all species groups irrespective of the model forms. When residual mean square values (RMS) were used to judge the importance of the variable lov, it showed that this variable contributed the biggest portion of RMS reduction for Groups LUF (8.1 out of 11.7 %) and LMUS (3.5 out of 4 %), from including terms additional to the basic form in the four selected final species groups for PT. ITCI data. The variable lov contributed about 2 out of 3 % RMS reduction for Group MeSF, and shared the same proportion with $G_{sp>d}$ for Group SmaS. The absolute statistical significance of including these additional variables is, of course, not tenable under traditional tests, because of the large amount of correlated data. Other statistical and graphical measures, such as SAS univariate outputs and residual patterns and distributions were, therefore, mainly used in examining models with various combinations of terms additional to the basic forms.

Other than lov, the following additional terms were also found to affect tree diameter growth.

- Altitude was evidently an important variable affecting the growth of the larger tree species (Groups LUF and LMUS), both in linear and non-linear form.
- A measure of tree dominance/tree competition index (tci) seemed to depend on functional form for larger tree species (Groups LUF and LMUS), but group dependent for smaller tree species group (MeSF). This variable was found to be significant for Group LUF in non-linear form, but did not materially affect diameter increment of this group in linear form. The variable tci was found to affect tree diameter increment for Group LMUS in linear form, but did not so in non-linear form. For Group MeSF, this variable significantly affected response variables both in linear and non-linear form.
- Interaction between variables tci and ci was found important for fitting both forms to data for Group LUF.
- Variable $G_{sp>d}$ was found to be important for Group SmaS irrespective of the model forms, and it seems also to be group rather than model form dependent.

The effects of site quality characteristics and geomorphology (variables SQ and geom) may be confounded with the variable lov, since most logged plots were located in better soils (SQ=1) and all logged plots were located in geomorphology of the same category

(geom=1). It was found that the inclusion of the variable SQ to Group LUF, and replacing variable lov with SQ for the three groups of LMUS, MeSF, and SmaS, did not give considerable improvement to the models, judged by the changes in the values of skewness, kurtosis, standard deviation, and residual ranges. Furthermore, the effect of the variable geom was not noticeable in the presence of variable lov. For this reason, these two variables were discarded from the equations.

4.2.2.2. PT. INHUTANI I data

The Gompertz projection form found best for the PT. ITCI data, did not prove to be a suitable function for the PT. INHUTANI I data, as demonstrated in the results section. Poor fits were shown (in this case clear positive skewing of residuals) for most species groups except for Groups MF and SF (with variable lov), which later were combined into Group MeSF (Appendices 4.19a-b).

The effects of additional terms examined are itemized below.

- a significant interaction effect between the variables ci and tci for Group LF confirmed the finding in modelling the PT. ITCI data for Group LUF (combined group of LF and UF).
- Variable lov proved to be important except for Group UF, which exhibited no noticeable effect of additional terms. It should be noted that only one among 64 species comprising Group UF was well represented, other species having little representation. This was suspected to be the reason why no additional terms could be detected to explain variability for this group. Moreover, the variable lov was the only additional term found to have considerable effect for the 5 groups of LS, MF, MS, SF and SS.
- Variable ci (sub-plot basal area excluding the subject tree) was also found to be important for Group US which was later combined with medium and small slower growing species groups (MS, SS), to form Group MSUS.
- These findings indicated that for PT. INHUTANI I data, the larger the number of species in a group having adequate representation (f.e. > 100 observations for each species), the more possibility that the effects of additional terms included in the models could be detected.

Five species groups were finally selected to be the most appropriate form of aggregation for the PT. INHUTANI I data in this study after carrying out statistical tests

(Tukey's test for comparison of groups variance) and graphical inspection. Although this statistical test might not provide a robust comparison between groups because of correlated data or because the variance between species may be inflated by group variance, graphical inspection appeared to confirm the result of the test.

As indicated earlier, exploring the most appropriate model for the PT. INHUTANI I data was beyond the scope of the present study. Effort was placed more on: analyzing how well the Gompertz projection form which best fitted the PT. ITCI data would characterize the PT. INHUTANI I data; ascertaining which variables affected diameter growth of this particular forest; whether or not the findings for the PT. ITCI data were repeatable for the PT. INHUTANI I models; and providing insight on what possible improvement or further research is needed. The most important question addressed was how well these models could serve as an interim tool for management. More elaboration is given in later sections.

4.2.2.3. Combined PT. ITCI/PT. INHUTANI I data

The Gompertz projection form demonstrated the consistency in quality of fit between faster and slower growing species groups for three different sets of species grouping except for Groups DF and LS in 10 species groups. This equation provided a better fit for faster growing species groups than the slower growing ones (Appendices 4.20a, 4.21a, and 4.22a). Clearly skewed residual patterns and distributions were found in most slower growing species groups, whereas for most faster growing species groups, this equation resulted in reasonable patterns of residuals.

Examination of additional terms included in the equations revealed the following :

- The effect of the dummy variable localities (loc) was found to be partly influenced by ways in which species were grouped, which resulted in differing proportions of the data (species composition and number of observations) for both localities for each species group in different sets of grouping. It was shown, especially through the significant effect of the variable loc for all slower growing species in both 4 and 8 species groups. The effect of this variable in the 10 species groups was not noticeable for Group DS; it was suspected that this resulted from a disproportionate composition of the data comprising this group between PT. ITCI and PT. INHUTANI I sets (6 and 94 % of the total data of Group DS for PT. ITCI and PT. INHUTANI I respectively). The effect of variable loc

was consistent for larger faster growing species, which was undetectable for Groups DF (in 4 groups) and LF (in 8 and 10 groups).

- The importance of variable lov was not found to be affected by ways of species grouping. The variable lov demonstrated its importance for all species groups except for small faster growing species (Group SF in 8 and 10 species groups).

- The effect of variable tci proved to be consistent for larger faster growing species, which was clearly perceivable for Groups DF (in 4 and 10 groups) and LF (in 8 and 10 groups).

- Sub-plot basal area greater than the subject tree ($G_{sp>d}$) exhibited consistent material effects for small slower growing species (Group SS) in the 8 and 10 species groups. This variable together with lov were not found to be affected by ways of species grouping.

- An expression of the combined effect of above and below ground competition (variable ci*tci), was also found to be partly influenced by ways in which species were grouped. This was shown through the effect of the variable ci*tci for Group SF. This variable was not found to be important for the Group SF in 8 species groups, but showed considerable effect in the 10 groups;

Comparison of residual patterns and other statistical measures (skewness, kurtosis, mean residuals, standard deviations, and residual ranges) of four, eight, and ten species groups (Tables 4.30, 4.32, and 4.34), suggested that species aggregations into eight and ten groups were preferable to the one into four groups. The choice between the model for eight or ten groups then depended on the following considerations.

- Model for 8 species groups was preferable to the one for 10 species groups, if least concentration of data in one group was considered (34 % of the total data for Group US in 8 groups and 45 % for Group NS in 10 groups).

- Model for 10 species groups was preferable to the one for 8 species groups, if separate models for species existed in both locations and the ones which existed in either location are required (6 groups for species which occurred in both locations, and 4 groups for species which occurred either in PT. ITCI or PT. INHUTANI I data sets).

4.2.3. Comparison between final selected models for PT. ITCI data and other individual tree based models developed for Indonesia's tropical rain forests

Further evaluation of the model developed in this study was done by comparison of the selected model for PT. ITCI (Equation [7.a] to [7.d]: Gompertz projection form) with Pambudhi's (1997) model, using logged plots data for PT. INHUTANI I, through examination of the residual pattern and distribution of each species group and growth trends for some individual species. Pambudhi's (1997) model was the only individual tree-based model that had been developed for tropical rain forests in Indonesia. He compared tree basal area increment of four species groups (*Shorea,* other dipterocarps, commercial non-dipterocarps, and miscellaneous) in logged-over forests in two locations of 1 and 5 years after logging at the first measurement and observed for approximately a 2 years period. He used linear models with distance-dependent and distance-independent competition measures for these 2 year growth data. Only the distance-independent model was used for comparison with selected models developed in this study. The PT. INHUTANI I data used to test these two models covered measurements of about 5 years after logging, and about 1 year after logging at first re-measurement. Only first and last re-measurement data was used for model comparison, so the interval length between these two re-measurements was 4 years. The two models were compared in the form of difference equations, since this form provided the best fit for the PT. ITCI data used in this study. Thus, Pambudhi's (1997) model needed to be expressed using d_2 (future diameter) as the response variable. The procedures used to transform Pambudhi's (1997) model to difference equation form, and for model comparison (Equations [7.a-d] and Pambudhi's, 1997 models) are presented in Appendix 4.23.

The results of comparison between both models were the following.

- The models selected for faster growing species groups for PT. ITCI (Equations [7.a] for Group LUF and [7.c] for Group MeSF) fitted reasonably well in terms of residual pattern and distribution, while the other two equations (Equations [7.b] and [7.d]) for slower growing species groups (Groups LMUS, and SmaS) exhibited clear positive skewing of residuals (Appendix 4.24a-d).
- Pambudhi's (1997) model (Appendix 4.23) resulted in a reasonable pattern of residuals for the Group commercial non-dipterocarps only, while the other three groups (*Shorea,* other dipterocarps, and miscellaneous) showed clear bias (Appendix 4.25a-d).
- It should be noted that both Pambudhi's (1997) model and the PT. ITCI model developed in this study, did not exhibit bias when fitted to the data used to build the models.

- Among the four species groups for the PT. ITCI data formed in this study, and four species groups of Pambudhi's (1997), only the Groups LUF and *Shorea* were directly comparable, since Group LUF consisted of mostly genus *Shorea.* This created some difficulties in comparing the models on a species group basis.
- Model comparison through confirming growth trends obtained from the equation for each species group with the actual diameter increment of individual species, may give some indications of how well a model fitted individual species (e.g Appendix 4.26a-d). This procedure, however, is tedious because of the large number of species, many of them with only a little representation.
- Model comparison by fitting both models to some individual species data showed :

    - Equation [7.b] which showed clear positive skewing of residuals when fitted to Group LMUS of PT. INHUTANI data (Appendix 4.24b), exhibited reasonable fit when confirmed with *Eusideraxylon zwageri* data (Appendix 4.26c); while for *Dipterocarpus tempehes,* Equation [7.b] was under predicting (Appendix 4.26b).
    - Pambudhi's (1997) model for the Group 'commercial non-diperocarps' was over-predicting when confirmed with *Eusideraxylon zwageri* data (Appendix 4.26c); while the one for the Group 'other dipterocarps', fitted reasonably for *Dipterocarpus tempehes* within the range of the data used to construct the model (up to 40 cm of diameter; Appendix 4.26b), which suggested further limitation of a linear model when it has to be extrapolated beyond the range of the data.

- Superiority of the Gompertz projection equation over the linear model was also shown by the performance of the two equations which were directly comparable (Groups *Shorea* and LUF), where the equation for Group LUF resulted in a better fit in terms of residual patterns and distribution of residuals than the one for the Group *Shorea* (Appendices 4.24a and 4.25a).

A most useful conclusion in all this model comparison for these forests can perhaps be obtained when other model components (mortality, regeneration and or recruitment) will be developed, so that the model can be evaluated as a whole. At this stage, comparison of the performance of each equation developed for each species group, and evaluation of the kinds of variable included in the equations in regard to applicability of the model, will be a useful guide to directing where further research on growth and yield of this type of forest should be made. For example, the question of how large a data coverage (in terms of stand and site conditions, as well as measurement period) is required, so that various factors affecting tree

growth of this type of forest can be confirmed. Furthermore, how competition should be expressed to obtain a certain degree of precision, taking into account the applicability of the models has to be ascertained.

4.2.4. Strengths and weaknesses of selected models

The study, as reported in earlier sections, demonstrated the superiority of the Gompertz projection form using years between measurements as a surrogate for age among the various functional forms tested to express diameter growth for the PT. ITCI data. This finding is a major contribution to the development of growth modelling for mixed species, particularly tropical rain forests where ages are indeterminate. Much individual tree based modelling has been developed for both plantation and natural forests, but most rely heavily on empirical linear models. Although some researchers have found that linear equations provide a good fit for their data, this study, given the available data, proved otherwise. This study showed that non-linear projection models were much less biased than the linear models over relatively long intervals, which represents a practical advance in recommended methodology for routine yield forecasting in forest management.

Linearized forms of the exponential decline function (Zeide, 1993) have also been used for modelling tree basal area increment for several individual species in tropical forests by Alder (1995) and resulted in reasonable fits in terms of residual distribution. The same form of equation showed clear bias when used for modelling diameter increment of species groups in this study. Alder (1995) argued that the shape of this function is more suitable for basal area than diameter increment. However, Zeide (1993) tested this equation for individual tree and pooled data and found that this equation performed well for diameter and height growth of individual trees, but poorly for the pooled data, judged by standard errors of estimate. Based on his comparison, Zeide (1993) concluded that the type of data affected performance of the function. The analogue of an exponential decline function (ED analogue) suggested by Shvets and Zeide (1996) was also fitted to the data, but did not show satisfactory results. Of the other kinds of exponential decline function defined by Zeide, the Chapman-Richards projection form proved to be difficult to converge when fitted to the data in this study, a disadvantage that has been found by other authors (e.g. Seber and Wild, 1989; Ratkowsky, 1990).

The particular deficiency in the best model found here was its low precision (large ranges of residuals), which suggested the need for further research. That such a large variation

was also found even within species, could also be ascribed to inaccurate measurement as well as to genetic and site variation. To improve the precision of such models, research may need to find urgently a better expression of competition factors and also to improve the measuring, checking and processing of data. The use of sub-plot (0.01 ha) as a unit to express competition factors may not be consistent with management procedures. However, it was found to be a better unit to express competition factors than a large plot level which varied in area from 0.25 – 2 ha. Moreover, with the data available, it was not possible to explore different unit areas to represent competition factors for the forest under study. This is one among several aspects that should be the subjects of future research.

The poor precision shown by the Gompertz projection form for most species groups of PT. INHUTANI I data, other than as an indication of the need to identify different functional forms, may also be symptomatic of the need for better data which have been re-measured over longer periods. It was shown by a better fit for the PT. INHUTANI I data alone, when both PT. ITCI and PT. INHUTANI I data were combined. As discussed in earlier sections, PT. ITCI data covered longer periods of measurement and wider ranges of site conditions, such as altitude, than the PT. INHUTANI I data. The Gompertz projection form which was found best in fitting the PT. ITCI data, showed poor fits for most species groups of the PT. INHUTANI I data. Results of fitting the Gompertz projection form to species groups in three different grouping (4, 8, and 10 groups), suggested that the larger the proportion of PT. ITCI data in each species group, the better was the model fit. This was shown particularly by better fits for faster than slower growing species groups (see Appendices 4.20a, 421a, and 4.22a), because the proportion of the PT. ITCI was larger than the PT. INHUTANI I data for most faster growing species groups and vice versa (see Appendices 3.7, 3.8, and 3.9 to 3.11).

A number of published individual tree based models rely on R^2 and standard deviation/standard error to judge model performance. Some authors seem to be reluctant to provide graphical plots of the pattern and distribution of residuals, which could give a clearer indication to readers of model precision than do R^2 and standard deviation/standard error measures alone. Some individual tree based models developed for dipterocarp forests show values of R^2 (Ong and Kleine, 1996), and R^2 and standard error of estimate (Wan-Razaly, 1988), as indicators of precision; but there was no explanation as to how good the residual patterns and distributions were for each model. Although these criteria may be suitable for certain types of data and for some models and parameter estimation techniques used, graphical plotting of residuals is equally important to provide a clearer idea of model fit in relation to the distributions of the data. The selected models from this study have been

evaluated in various ways using criteria stated in section 3.3, giving a clearer indication to the readers regarding quality of the model.

Comparison between the four species groups of PT. ITCI data developed in this study and Pambudhi's (1997) model using independent data, showed that two out of four groups formed in this study were found to fit reasonably well to the data (Appendices 4.24a-d), while only one out of four groups formed by Pambudhi (1997) fitted the data reasonably well (Appendix 4.25a-d), despite the data used here to test the models being more similar to the data used for constructing Pambudhi's (1997) model in terms of measurement period and stand condition (logged-over plots). This finding could be a further indication of the superiority of the Gompertz projection equation over linear models. It was also demonstrated by the performance of the two equations which were directly comparable (Groups *Shorea* and LUF), that the equation for Group LUF resulted in better fits in terms of residual patterns and distribution of residuals than the one for the Group *Shorea* (Appendices 4.24a-d and 4.25a-d).

4.2.5. Insight gained from studiying the PT. ITCI and PT. INHUTANI I data and further research required

Results from fitting the Gompertz projection form to three different data sets, indicated that this function has a potential to be used for individual tree based modelling for mixed species with unknown ages. Despite relatively poor precision and some bias for most species groups for the PT. INHUTANI I data alone, Group MeSF showed reasonable fit, which suggests that improvement is possible when more and better data are available. The model with combined data may be more appropriate for routine management forecasts of PT. INHUTANI I forest at this stage. Identifying a sigmoid function for this data set other than the Gompertz form may help to find even better models for characterizing diameter growth in this particular forest.

Stand attributes in the form of competition measures and locality factors are important driving variables affecting tree growth. Dummy variables separating logged and unlogged plots were also found to be strong predictors for individual tree diameter growth. Some researchers studying growth of logged over forests have found time since logging materially affects tree growth. Results of including time since logging in tree growth models should be interpreted with caution, however, especially when this variable is obtained from separate locations with different times since logging, as this effect may be influenced by site

characteristics and also stand basal area. Moreover, there has not been conclusive evidence showing how long the positive effect of gap opening following logging will continue to exist. A growth study in Brazilian Amazon tropical rain forests found that the positive effect of logging on growth of some species ceased three or four years after logging, but other species showed longer positive effects of gap opening after logging (Silva *et al.,* 1989). Nguyen-The *et al.* (1996) found no difference in growth rates between two logged-over forests (2 years and 15 years after logging) in Berau (East Kalimantan). For this reason, time since logging was not included in the model developed in this study, but logged and unlogged plots were separated through use of dummy variables, and stand attributes were incorporated in the models. This suggested that further research into other more useful time-lag variables could prove fruitful. The data used in this study covered times since logging up to 22 years, but the variable lov (1 for logged and 0 for unlogged plots) still showed positive sign which indicate higher tree growth in logged than unlogged plots. The inclusion of stand attributes such as sub-plot basal area excluding the subject tree (ci), sub-plot basal area of trees larger that the subject tree ($G_{sp>d}$), a measure of tree dominance (tci), and interaction between ci and tci (ci*tci), may have been able to compensate for lack of firm dates of logging. Another possible reason was the fact that most logged plots were located in better soil than unlogged plots, which confounding factor also contributed to higher tree growth in logged than unlogged plots.

Many researchers have used stand basal area (G) and surrounding basal area greater than the subject tree ($G_{>d}$) to express competition factors for individual tree distance-independent based modelling. This study demonstrated that a measure of tree dominance tci ($1 - G_{sp>d}/G_{sp}$) and its interaction with the variable ci namely ci*tci, were better measures of expressing competition factors for larger tree species groups, while basal area greater than the subject tree was found to be important for small slower growing species group (Group SS). It is suggested that for larger tree species groups in the forest under study, both above and below ground competitions were limiting factors for tree diameter growth; while for the small slower growing species group, above ground competition (competition for light) was the only limiting factor for their diameter growth. The variables $G_{>d}$, tci, and ci*tci might be highly correlated since the two latter variables were cross-products of the first and other variables, which could be the potential source of multicollinearity. However, using criteria in page 60 (linear model with PROC REG) and page 61 (non-linear model with PROC NLIN), and other criteria set out in section 3.3.1 of Chapter 3, these variables were best represent competition factors within small unit area (10 x 10 m^2) for the data used in this study.

Altitude above see level (variable alt) has been used in some individual tree models for sub-tropical species, but the use of this variable for individual tree based modelling for tropical mixed-species forest was not found to have been reported in other publications. This study proved the importance of the variable alt for larger tree species groups for the PT. ITCI data. It indicated the importance for selecting tree growth plots to cover a wide range of altitude.

The selected species groupings for PT. ITCI data were found to be best for the purpose of this study, and the model demonstrated better performance when compared with Pambudhi's (1997) model using independent data. Although this result could also be influenced by the form of model used, and may also be data specific, this finding provided an alternative way of grouping species for modelling dipterocarp forests which had previously relied mostly on commercial criteria for aggregating into groups. Until all model components able to be developed so that the model can be evaluated as a whole, it is still difficult at this stage to suggest which way of grouping species is considered the best, but there is a good evidence given here that any individual situation would benefit from the approach to grouping that was adopted and recommended as part of this study.

The great variability in growth rates of tropical species, and the large number of species with little representation were both found to add difficulties to modelling the growth of this type of forest satisfactorily. Imminent research, should perhaps better concentrate on species with large representations (commercially or ecologically important species), and to group all other species with little representation on their own or depending upon the importance of species in this category, they may be combined with the most similar existing groups.

This study has produced several positive advances in knowledge about modelling diameter growth of trees in a specified tropical forest in East Kalimantan and several more which could be more accurately described as negative findings.

4.2.6. Implications from the results of the study for management of tropical rain forests in Indonesia

The study, as stated in the previous section, has generated both positive and negative findings in term of its relevance to management of production forests in tropical rain forests. The best growth model obtained from the study, with its strengths and weaknesses, offers a

useful interim tool for forest management which should be viewed as a better method for predicting production capability and/or future stand structure than simple diameter average that is currently used as the basis for calculating production capability for the next cutting cycle.

Smaller bias was shown by the Gompertz projection form than the linear models over longer interval especially for larger tree species groups (where most commercial tree species fall), and this projection form should be used for routine yield forecasting in forest management. This finding also confirmed recommended interval length between measurement for growth studies in tropical rain forests, where diameter growth rates may vary between 1 to 20 mm/year for a range of species. Low increment between 1 to 2 mm/year are usually associated with small understorey trees. Emergent or upper canopy species of larger sizes generally have increments above 5 mm, which can be determined with reasonable precision over a 5-year interval (Alder and Synnott, 1992). Species group specific competition factors found in this study for example, tci for larger faster growing species groups (mostly commercial tree species) and $G_{>d}$ for small slower growing species, can be used as a guide to determine what type of silvicultural treatments is needed for certain species groups of interest. These competition factors for some reasons, however, were determined using 10m x 10m (0.01 ha), which may limit its application.

Shape and size of plots are among critical issues in forest management forecast using growth and yield models. Square plots or the ones of broad rectangular shape (length/width <2) have been widely used for PSP_s work in tropical rain forests. In dense forests, they are faster to demarcate than circular plots, and the square shape minimizes edge effects (Alder and Synnott, 1992). The principle that governs the choice of plot sizes is that, in general, with any sampling, precision of estimates increases with the number of sample points irrespective of size. This is because the standard error of an estimate is equivalent to the standard deviation of the population divided by the square root of the number of samples. Hence, standard error declines directly as the number of samples increases (Lanly, 1981). However, tropical rain forest is heterogeneous at the local scale, so variance increases as plot size decreases. If PSP_s are established as part of a system of CFI which also involves TSP_s and PSPs, then the shape and size of the TSP_s and PSP_s should be compatible. Otherwise, projection and regression involving per hectare units may be biased, especially where competition indices are included (Alder and Synnott, 1992). It is frequently found in practice that TSP_s and PSP_s are established without any formal linkage, and by different organizations. PSP_s are often regarded as a research activity, while forest inventory may be a component of

forest management, and so plot size and shape are frequently incompatible. In this case, every effort should be made to adopt a common plot sub-unit, to allows growth and yield projections to be made from this basic sub-unit without involving an unknown bias due to different bases for calculating competition indices on the PSPs and TSPs. However, the plot size that best represents competition and is efficient from a sampling point of view can only be determined after future study. The final plot size is likely to be a compromise between sampling efficiency and good representation of competition.

Reliable growth models are pre-requisites for predicting sustainable yield capabilities of forests, of which the projected outputs are used to evaluate and adjust management options to achieve sustained yield. The best growth model obtained from this study, as explain in earlier sections, is a preliminary one. Further research is still needed in order to improve model quality and its applicability for management purposes. Other model components need to be developed to be able to provide more useful information regarding future stand structure. Plot sizes that best represent competition factors and are efficient from a sampling point of view need to be determined by future studies. Although the variable lov (separating between logged and unlogged plots) was found to be an important additional term in the model for all four final selected species groups of PT. ITCI data and most groups of PT. INHUTANI I data, this variable need to be evaluated further. It is premature in this stage to suggest likely model performance for long-term projection to determine sustained yield, since the outcome of the study has indicated that more work still needs to be done and resources to be invested to refine the model.

As the results of the study have been presented and discussed, the main findings and conclusions are set out in summary in the final following chapter.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1. SUMMARY

A reliable means of providing production and stand dynamics forecasts is central to managing production tropical rain forests in Indonesia. Growth models have been shown to offer a reliable way to, for example: examine harvesting options, determine sustainable yield capability and predict future stand structure.

The study was conducted with the aim to develop a suitable growth modelling methodology, in order to improve planning of timber harvests in the short and medium terms, and enhance forest management generally, thus assisting in the sustainable management of a selected area of Indonesian rain forest.

Permanent growth plot data in PT. ITCI and PT. INHUTANI I forests were used to study the dynamics of forest development over time. The PT. ITCI data consisted of 14 plots ranging in area from 0.25 to 2 ha and 1025 sub-plots each of 0.01 ha, most of which had been measured and re-measured from 1976 to 1993. The PT. INHUTANI I data consisted of 12 plots of 4 ha, each of which had been divided into squares of 1 ha, in which measurements had been made from 1991 to 1996. A data set consisting of 4105 individual trees greater than 15 cm in diameter at breast height or above buttresses/irregularities, and 491 species codes, was able to be derived from the PT. ITCI data base. The data set derived from the PT. INHUTANI I data base consisted of 640 species codes for 13063 individual trees greater than 15 cm in diameter at breast height or above buttresses/irregularities.

Individual tree-based distance-independent modelling was used to model diameter growth in these two localities. In selection cutting, which is the silvicultural system used in Indonesia's tropical rain forests, guidelines from the Ministry of Forestry determine the minimum diameter at breast height or above buttresses/irregularities of trees of various species that are allowed to be cut. For this purpose, individual tree based models, which maintain species identity and which utilize diameter growth as the response variable, have practical advantages.

Several difficulties in the existing data base for PT. ITCI as explained in page 35 were evident at the outset: irregularity of measurement intervals; variability of measurement

frequencies among the growth plots; moving the height at which girth measurements were made; zero increment and excessive changes in diameter (too large increment and/or decrement) between consecutive measurements for a number of tree species. All these added difficulty to modelling tree growth of this particular forest satisfactorily.

The plots of PT. INHUTANI I were established mainly for studying the impact of different logging techniques and intensities on the development of residual stands and their regeneration. The data did not cover as wide ranges of altitude as in the PT. ITCI population (all plots were located at altitudes lower than 100 metres above sea level). Furthermore, the data covered only very short periods of measurements, that is 4 times within 5 years, and logging had taken place before the first re-measurement.

With these types of data, more effort in obtaining a model which can provide insight into how to effect its future improvement is desirable, as long as this helps in understanding the system being modelled better and in providing a useful interim tool for management purposes. Early examination through plotting the selected models developed for PT. ITCI to PT. INHUTANI I data exhibited bias. For this reason, separate models were developed for each as well as for the two localities combined. The model developed for each locality generated research findings which helped to gain insight into what further research or model improvement, specific to the forest being managed, is needed. The combined model, together with the separate models for each locality, have especially helped to identify which variables strongly affect diameter growth of the forests in the two localities.

Modelling in this study dealt with a very large number of species, many of which had little representation. Moreover, no single species among the 491 for PT. ITCI represented more than 7 % of the total number of observations; and of the 640 species codes for PT. INHUTANI I, no single one represented more than 4 % of the total number of observations in each data set. Hence, for the purpose of modelling, these species had to be aggregated. Much effort in the research was directed at exploring various ways for grouping species using criteria which suit what is available in the data and what intended use there is for the model.

An empirical approach using ecological criteria such as maximum attainable size (potential to occupy certain canopy layers) based on published and observed data, local knowledge, and growth rates, with continual re-examination and re-evaluation during the process of modelling (through statistical and graphical analysis) was used in this study. The 491 species of PT. ITCI and 640 species of PT. INHUTANI I were aggregated initially into eight species groups of large, medium, small, and other tree species, each of which was

broken down into faster and slower growing species. Through several steps of examination, four and five final species groups were selected for PT. ITCI and PT. INHUTANI I data respectively.

Clear differences in level of detail in species identification between the PT. ITCI and PT. INHUTANI I data, caused difficulty in grouping species when both data sets were combined. Many species in the PT. INHUTANI I data were identified up to family or genus level only, and so, it was possible that trees which in PT. INHUTANI I data were under the same family or genus name, fell into different species names in the PT. ITCI data. Combined PT. ITCI and PT. INHUTANI I data comprised 1013 species: some 110 species existed in both localities, 97 of which fell into the same groups when using faster and slower growing criteria. Among 13 species which fell into different groups (faster or slower growing species), 9 species in the PT. ITCI data had too little representation to be tested; 2 species in the PT. ITCI data did not show clear bias when the chosen model was fitted to these species; and 2 other species had too little representation in both locations. The thirteen species were then included in either other faster or slower growing species.

Other slower growing species shared the biggest proportion in both PT. ITCI and PT. INHUTANI I data. Therefore, three different ways of aggregating species were examined for the combined data, in order to identify which sets of grouping provided the best fit for the data, and had the least concentration of data in one group. The first grouping consisted of 4 species groups (faster and slower growing dipterocarps and non-dipterocarps); the second grouping comprised 8 species groups (large, medium, small, and other tree species : faster and slower growing); while the third grouping accommodated 10 species groups, 6 groups of which existed in both localities (large, medium, and small tree species : faster and slower growing) and 4 groups existed either in PT. ITCI or PT. INHUTANI I data only (dipterocarps and non-dipterocarps : faster and slower growing).

Aggregating species pertaining to the combined data into 4 and 10 species groups (the first and third ways of grouping) resulted in 60 % and 45 % of the total number of observations respectively falling into the group of slower growing non-dipterocarps. Species aggregation into 8 groups (the second way of grouping), yielded the least concentration of data in one group among the earlier two ways of grouping (34 % for other slower growing species group). The three different ways of species grouping were each also found useful in examining which variables were consistently affecting the tree diameter growth and which ones were likely influenced by ways of species grouping.

Modelling was started using PT. ITCI data, because, as has been stated previously, these data covered longer measurement periods, provided more detailed species identification, and had a wider range of locality factors such as altitude, than did the PT. INHUTANI I data. Various techniques were explored in order to derive the best possible tree diameter growth models for this particular forest from statistical, logical and biological points of view, taking into account the intended uses of the models and information available to build the models.

Of the various linear and non-linear equations analyzed, the best models representing each model type were identified and comparisons made between the two best models of their type. Superiority of one over another model type was examined in the following ways:

In projection form (d_2 as the response variable)

1. graphs of mean residuals for predicted diameter (d_2) over several actual interval lengths between measurements;
2. plots of residuals obtained from transformation of the fitted diameter increment function (d_i) to projection form (d_2); and statistical measures obtained through univariate procedure;

In increment form (d_i as the response variable)

1. scatter plots of residuals against predicted d_i,
2. graphs of the mean residuals for predicted diameter increment (d_i), transformed from the chosen linear and non-linear models,
3. graphs of the chosen models of both model types in the form of diameter increment (cm/year) for various initial tree diameters, competition and locality factors.

Modelling was then extended to the PT. INHUTANI I and combined PT. ITCI/ PT. INHUTANI I data. The best model form obtained from modelling the PT. ITCI data, namely a Gompertz projection form (combined with stand attributes and locality factors) was used for modelling these latter two data sets. Stand attributes and competition measures such as: G_{sp}, ci, $G_{sp>d}$, tci, and interaction between ci and tci, as well as lov; were examined for modelling PT. INHUTANI I data. The dummy variable loc (localities) which took up values of 1 for PT. ITCI and 0 for PT. INHUTANI I plots was included in modelling the combined data, the sign of the coefficient for which could be positive or negative.

Qualities of each of the three models (PT. ITCI, PT. INHUTANI I, and combined PT. ITCI/PT. INHUTANI I) were evaluated through statistical and graphical analysis, from

logical and biological points of view, as well as practical considerations. The PT. ITCI model was chosen to be compared with other individual tree-based model developed for a dipterocarp forest (Pambudhi, 1997), using logged-over plots data of PT. INHUTANI I. Model fits were examined mainly through plotting residuals (d_{2act}-d_{2pred}) against predicted future diameter (d_2) for each species group. The applicability of the two models for management purpose in terms of variables included in the models was also compared.

5.2. CONCLUSIONS

PT. ITCI data

An empirical approach using ecological criteria such as maximum attainable size (potential to occupy certain canopy layers) based on published and observed data, local knowledge, and growth rates, with continual examination during the process of modelling (through statistical and graphical analysis), was found to offer the most appropriate way to aggregate species of PT. ITCI data. The final four species groups of : large and other faster growing species (LUF); large, medium and other slower growing species (LMUS); medium and small faster growing species (MeSF); and small slower growing species (SmaS), was found to be more flexible than species grouping in models developed by earlier researchers for dipterocarps, which tended to separate them on the basis of dipterocarps and non-dipterocarps, or between commercial and non-commercial species. The species grouping developed in this study allowed dipterocarps to fall into the first 3 groups, while each group, except Group SmaS, consisted of both commercial and non-commercial species. Fitting the chosen model for each species group to individual species with reasonable numbers of observations indicated the soundness of this grouping.

Of the various growth model functional forms examined for PT. ITCI data, analysis showed that the following valuable indications could be drawn.

1. Altitude was an important predictor for diameter growth of larger tree species irrespective of model forms and ways of grouping species.
2. In the absence of the variable logged or unlogged/virgin (lov), the effect of soil characteristics (SQ) expressed as poor and better soil was significant for all species groups except for small tree species. The variable SQ was perhaps also confounded with

the variable lov, since better soil quality was found mostly in logged-plots (5 out of 7 plots).

3. For the four final selected species groups (LUF, LMUS, MeSF, SmaS), with the variable lov present in the models, soil characteristics were found to have a significant effect only for Group LUF. However, the inclusion of this variable even for that group alone yielded only a very small improvement to the model.
4. At the plot level, accumulated tree basal area (G) and or basal area greater than the subject tree ($G_{>d}$ or $G_{>d}/\ln(d+1)$) had a significant effect on growth of some species groups, while at the sub-plot level with 4 final species groups, the influence of accumulated tree basal area was in a form which excluded the subject tree (ci), a measure of tree dominance (tci), and an interaction between the variables ci and tci.
5. For small slower growing species, accumulated tree basal area greater than the subject tree $G_{>d}$ (or $G_{>d}/\mathrm{Ln}(d+1)$) at plot and sub-plot level and lov were important variables affecting diameter growth.
6. Another locality factor, geomorphology (geom), was also examined, but this variable did not prove to be an important factor affecting diameter growth for all species groups in the presence of variable lov. The variable geom might also be confounded with the variable lov, since all logged-plots were located in the same category of geomophology.
7. Of the various combinations of predictor variables which have been explored, the final decision on which ones to include in the models was determined by statistical, logical, and biological criteria as well as practical considerations.
8. Square root transformation of the response variable (diameter increment) was found to be the best form of the linear model and the Gompertz projection form (d_2) of the non-linear models tested. The general form of the two model types is presented below :

$$\sqrt{d_i} = f\,(d,\ \textit{stand attributes and locality factors})$$
$$d_2 = f\,(d_1,\ t_2\text{-}t_1,\ \textit{stand attributes and locality factors})$$

An interaction between a measure of tree dominance (tci) at the stand (sub-plot) level and accumulated tree basal area excluding the subject tree (ci) was an important finding revealed in this study. This variable indicated the existence of a combined effect of above and below ground competition for Group LUF (large and other faster growing species). Accumulated basal area of trees larger than the subject tree was found important only for small slower growing species (Group SmaS). Stand condition separating plots which had been logged previously or not (lov), was found to be a strong predictor variable for all species

groups. The variable tci alone was found to have a profound effect on diameter growth of faster growing species (Groups LUF and MeSF).

The results of comparing linear and non-linear models can be summarized as follows.

- Both model types were under-predicting over short intervals (< 3 years); non-linear (Gompertz projection forms) had slightly higher mean residuals than linear models. For longer intervals, non-linear ones performed better. This suggested some superiority of non-linear over linear models for longer periods of prediction, which represents a major advance in scientific knowledge from a practical point of view.
- The Gompertz projection form was relatively unbiased over longer intervals (4-6 years) and ranges of diameter classes for larger tree species groups.
- Univariate output obtained from the Gompertz (non-linear) form, and the one from transformation of the fitted diameter increment function d_i (linear model) for each species group to projection form d_2 and graphical plots of residuals in the form of d_{2act}-d_{2pred}, suggested the non-linear form to be preferable to the linear form.

This study revealed that a non-linear sigmoid function in projection form using interval length between measurements rather than ages to express the variable t_2-t_1, provided better fits in modelling diameter growth among all the other functional forms examined. When using various criteria to evaluate the relative worth of linear and non-linear models, this study has also revealed the superiority of the non-linear projection form over the linear increment function.

Comparison of selected models for four species groups of PT. ITCI data developed in this study (Gompertz projection form) with Pambudhi's (1997) model (linear model) using independent data (PT. INHUTANI I data), suggested superiority of the Gompertz projection equation over Pambudhi's linear models judged by residual patterns and distributions of the two types of model. Furthermore, the models developed in this study used predictor variables which proved to be more flexible in terms of applicability than the ones suggested by Pambudhi (1997) e.g. codes of times since logging (1 for 1 year and –1 for 5 years after logging) which restricted the use of the models.

PT. INHUTANI I data

Five species groups were finally selected to characterize diameter growth for PT. INHUTANI I data. Results of fitting the Gompertz projection form to these data did not prove

its suitability for most species groups of the PT. INHUTANI I data, shown by clear positive skewing of residuals for most species groups except for Group MF and SF (with variable lov), which were later combined into Group MeSF.

Among the additional terms examined, a significant interaction effect between the variables ci and tci for Group LF confirmed the finding in modelling the PT. ITCI data for Group LUF (combined group of LF and UF). The variable lov was found to be important for 7 species groups (faster growing species groups except UF and all slower growing ones), and was the only additional term having considerable effect for 5 groups, namely LS, MF, MS, SF, and SS. Group UF was the only group which did not show a noticeable effect of additional terms.

Combined PT. ITCI /PT. INHUTANI I data

Results of fitting the Gompertz projection form to the combined data indicated that species aggregation into 8 and 10 groups were found to be preferable to aggregation into 4 groups as judged by their residual patterns and distributions, and statistical criteria used to evaluate the models.

A measure of tree dominance (tci) did not show significant effect for the PT. INHUTANI I data, but this variable and its interaction with variable ci were found important for larger faster growing species for both the PT. ITCI and combined data. The existence of a combined effect of above and below ground competition was evident for larger faster growing species, as depicted by the similar finding when PT. ITCI and PT. INHUTANI I data were modelled separately. The interaction between variables ci and tci was found significant for Groups LUF for PT. ITCI data and LF for PT. INHUTANI I data.

A consistent effect of a measure of tree dominance (tci) and its interaction with basal area of surrounding trees in sub-plot (ci*tci), and the locality dummy variable (loc), were demonstrated by some larger faster growing species groups in the combined data. The variables tci and ci*tci were found to affect growth for Groups DF (in 4 groups) and LF (in 8 and 10 groups), while the effect of variable loc for both Groups DF and LF in the same grouping (in 4 groups for DF, 8 and 10 groups for LF) was undetectable. For other species groups of the combined data, the effect of variables loc and ci*tci seemed to be influenced by ways of grouping species. Accumulated basal area of trees larger than the subject tree in sub-plot proved to be an important competition factor affecting diameter growth of small slower growing species for both the PT. ITCI and combined data.

Conversely, the result of including dummy variable loc (localities) 1 for PT. ITCI and 0 for PT. INHUTANI I in the equation, did not show a significant effect on predicted d_2 for most larger faster growing species, particularly the groups DF (in 4 groups), LF (in 8 and 10 groups), and NF (in 10 groups). Small faster growing species (Group SF) showed no significant effect of variable lov; localities (variable loc) seem to be affecting diameter growth of this group more strongly than the variable lov, as depicted by the significant effect of the variable loc in the 8 and 10 groups.

5.3. RECOMMENDATIONS

PT. ITCI data

The interim model recommended for management use as a result of this study is very much a preliminary one. The models main deficiency is shown up in the relatively large spread of residuals. Residual ranges of ± 4 cm were shown for Group LFUF's future diameter (d_2); ± 5 cm for Group MeSF's; and ± 2 cm for Groups LMUS's and SmaS's. Despite these large ranges of residuals, most observations lay between ± 2 cm for faster growing species (Group LFUF and MeSF) and ± 1 cm for slower growing species (Groups LMUS and SmaS). A large variation in growth rates occurred even within species, which reinforces the need for further research.

Irregularity of measurement interval, variability of measurement frequencies among the growth plots, and moving heights of measurements at different times are some aspects which need serious attention in the near future. These conditions have constrained rejection of suspicious plot data and/or between consecutive measurements for modelling purposes, because the number of growth plots are too few and the re-measurement period has not been long enough. To capture the changes caused by environmental factors better, regular measurements intervals and as far as possible the same frequencies of measurement among the growth plots are necessary. Moving heights of measurements is unavoidable, and species which develop buttresses are generally important commercially or ecologically; it is important, therefore, to record measurements at the old and new heights.

Apart from the field measurement aspects, other difficulties in dealing with the data sets included tree measurement records with unreasonably large increments or decrements. Too large an increment may be caused by measurement error (e.g. measuring trees at the same height as previous measurement for trees which have developed buttresses/

irregularities), as well as recording errors. The main cause of a large decrement perhaps was recording error. Large decrement because of measuring trees at different height as a result of buttress development could be detected from records of measurement height. It implies that correct recording and proper checking and management of the data are as important as qualities of field measurements.

PT. INHUTANI I and Combined PT. ITCI/PT. INHUTANI I data

Despite some clear bias resulting from fitting the Gompertz projection form to PT. INHUTANI I data, a reasonable fit was shown for Group MeSF, and better fits were obtained for most species groups of the combined data. This suggested that further improvement in the PT. INHUTANI I model obtained in this study is possible when more and better data become available. At this stage, the model for the combined data is probably more appropriate for routine management forecasts.

Exploring the most appropriate model for the PT. INHUTANI I data was beyond the scope of the present study. Identifying other functional forms for these data from more research may help to find the best possible models for this particular forest.

PT. ITCI, PT. INHUTANI I and the combined PT. PT. ITCI/PT. INHUTANI I

The models developed in this study have not included other components of growth models (mortality, regeneration and or recruitment) necessary for yield forecasting of tropical rain forest. Based on the findings in modelling survivor growth in this study, efforts need to be concentrated firstly on improvement of this diameter model with more and better data to be added to model development. Routine management checks should be used for monitoring the reliability of the models at this early stage instead of wasting valuable re-measured data. Other efforts should be directed at constructing mortality and recruitment models only when more and better data became available.

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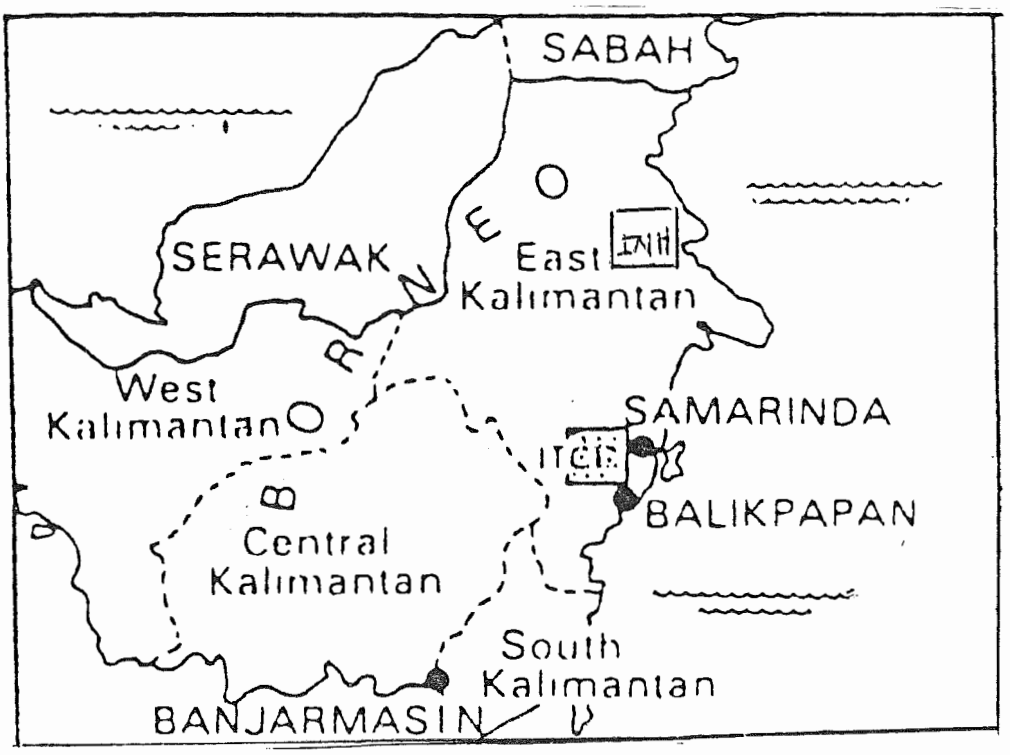
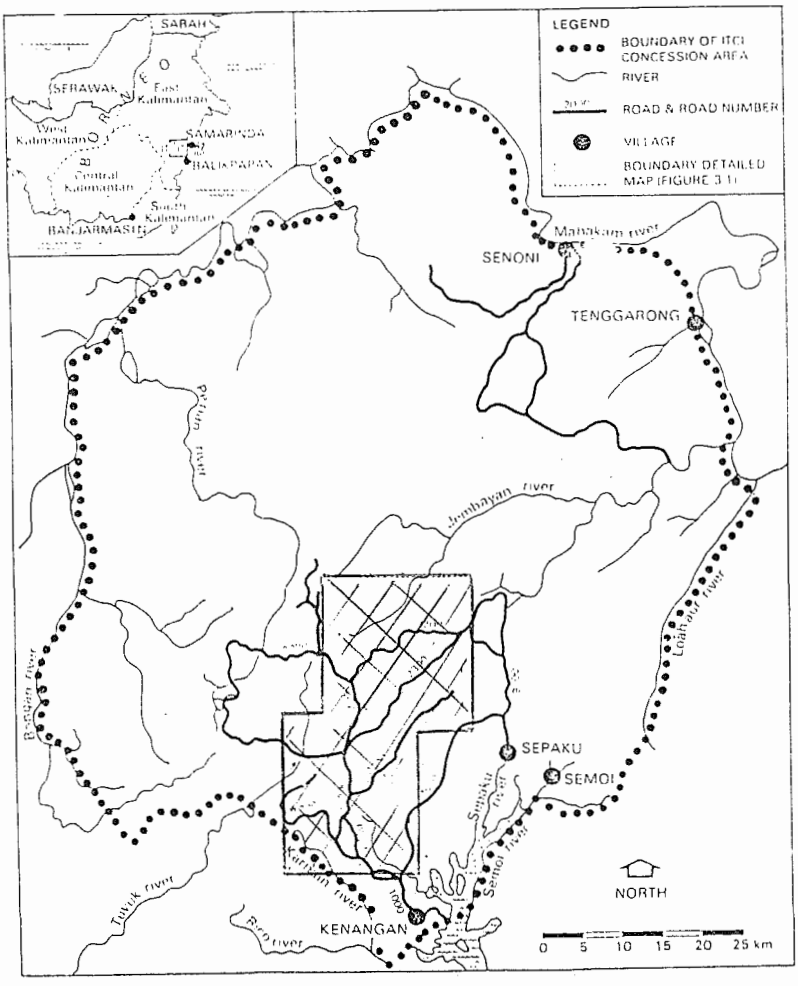
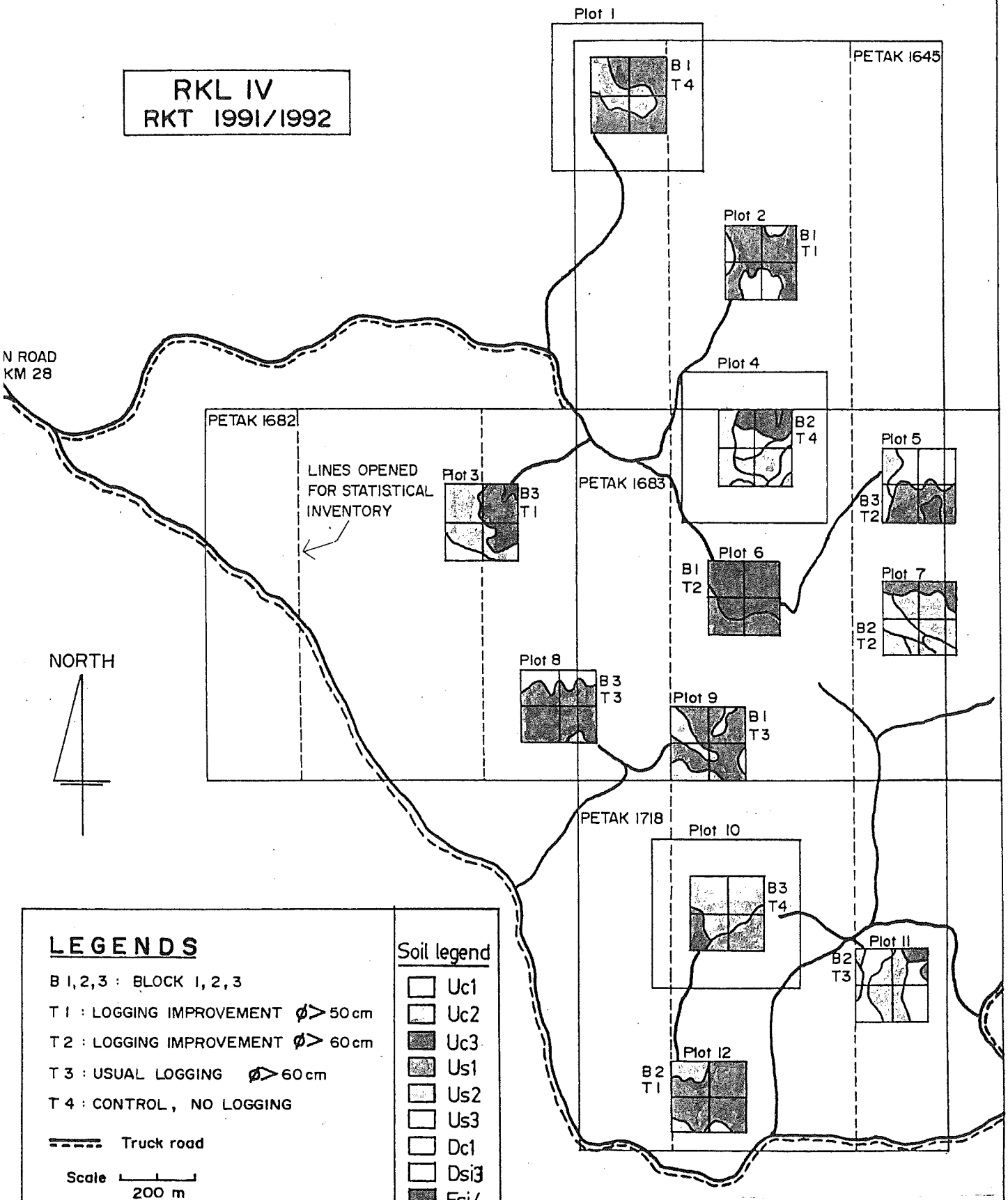
Appendix 3.1. Locations of PT. ITCI and PT. INHUTANI I in East Kalimantan



Appendix 3.2. Plot location in PT. ITCI concession area (from Bremen *et al.*, 1990)



Appendix 3.3. Plot layout and soil map of PT. INHUTANI I



From Soemaryono (1996)

Appendix 3.5. List of species codes and names for each of final selected species groups for PT.ITCI data

Large and other faster growibng species (Group LUF)

1	LF	Als	ang	*Alstonia angustiloba*
2	LF	Als	int	*Alstonia intermedia*
3	LF	Aqu	mal	*Aquilaria malaccensis*
4	LF	Art	ela	*Artocarpus elasticus*
5	LF	Atu	exc	*Atuna excelsa*
6	LF	Cal	mac	*Calophyllum macrocarpum*
7	LF	Can	meg	*Canarium megalanthum*
8	LF	Cas	luc	*Castanopsis lucida*
9	LF	Dia	pla	*Dialium platysepalum*
10	LF	Dip	gra	*Dipterocarpus grandiflorus*
11	LF	Dip	hum	*Dipterocarpus humeratus*
12	LF	Dry	lan	*Dryobalanops lanceolata*
13	LF	Dye	cos	*Dyera costulata*
14	LF	End	mai	*Endiandra maingayi*
15	LF	Eug	flo	*Eugenia flosculifera*
16	LF	Fig	sup	*Ficus superba*
17	LF	Her	jav	*Heritiera javanica*
18	LF	Her	sim	*Heritiera simplicifolia*
19	LF	Koo	exc	*Koompassia excelsa*
20	LF	Lit	cyc	*Lithocarpus cyclophorus*
21	LF	Lit	ell	*Litsea elliptica*
22	LF	Lit	gra	*Lithocarpus gracilis*
23	LF	Lit	wal	*Lithocarpus wallichianus*
24	LF	Oct	sum	*Octomeles sumatrana*
25	LF	Pal	her	*Palaquium herveyi*
26	LF	Pal	mai	*Palaquium maingayi*
27	LF	Pen	tri	*Pentace triptera*
28	LF	Pom	pin	*Pometia pinnata*
29	LF	Pte	jav	*Pterospermum javanicum*
30	LF	Sca	mac	*Scapium macropodum*
31	LF	Sho	gib	*Shorea gibbosa*
32	LF	Sho	gra	*Shorea gratissima*
33	LF	Sho	hop	*Shorea hopeifolia*
34	LF	Sho	joh	*Shorea johorensis*
35	LF	Sho	lae	*Shorea laevis*
36	LF	Sho	lam	*Shorea lamellata*
37	LF	Sho	lep	*Shorea leprosula*
38	LF	Sho	mac	*Shorea macrobalanos*
39	LF	Sho	muj	*Shorea mujongensis*
40	LF	Sho	ova	*Shorea ovalis*
41	LF	Sho	paa	*Shorea parvistipulata* (Ashton)
42	LF	Sho	paf	*Shorea parvifolia*
43	LF	Sho	pas	*Shorea parvistipulata* (Meijer)
44	LF	Sho	pau	*Shorea pauciflora*
45	LF	Sho	pol	*Shorea polyandra*
46	LF	Sho	smi	*Shorea smithiana*
47	LF	Tri	mal	*Triomma malaccensis*
48	UF	Agl	spe	*Aglaia spectabilis*
49	UF	Ard	NK	Fam. *Myrsinaceae*
50	UF	Art	NK	Fam. *Moraceae*
51	UF	Can	NK	Fam. *Burseraceae*
52	UF	Cas	NK	Fam. *Flacourtiaceae*
53	UF	Cas	sch	*Castanopsis schefferiana*
54	UF	Cya	NK	Fam. *Annonaceae*
55	UF	Deh	NK	Fam. *Lauraceae*
56	UF	Dia	ind	*Dialium indum*
57	UF	End	NK	Fam. *Lauraceae*
58	UF	Geu	far	*Geunsia farinosa*
59	UF	Glo	NK	Fam. *Euphorbiaceae*
60	UF	Glu	NK	Fam. *Anacardiaceae*
61	UF	Gre	NK	Fam. *Tiliaceae*
62	UF	Koo	NK	Fam. *Leguminosae*
63	UF	Lit	NK	Fam. *Lauraceae*
64	UF	Mac	NK	Fam. *Euphorbiaceae*
65	UF	Mag	NK	Fam. *Magnoliaceae*
66	UF	Mag	ele	*Magnolia elegans*
67	UF	Mic	cin	*Microcos cinnamomifolia*
68	UF	Nep	NK	Fam. *Sapindaceae*
69	UF	Par	spe	*Parkia speciosa*
70	UF	Pen	NK	Fam. *Tiliaceae*
71	UF	Pol	NK	Fam. *Annonaceae*
72	UF	Que	arg	*Quercus argentata*
73	UF	Sco	spi	*Scolopia spinosa*
74	UF	Sem	NK	Fam. *Anacardiaceae*
75	UF	Sho	NK	Fam. *Dipterocarpaceae*
76	UF	Xan	aff	*Xanthophyllum affine*
77	UF	Xyl	fer	*Xylopia ferruginea*

Large, medium, and other slower growing species (Group LMUS)

78	LS	Aga	bor	*Agathis borneensis*
79	LS	Ala	rid	*Alangium ridleyi*
80	LS	Als	ins	*Alseodaphne insignis*
81	LS	Ani	cos	*Anisoptera costata*
82	LS	Ani	mar	*Anisoptera marginata*
83	LS	Art	rig	*Artocarpus rigidus*
84	LS	Atu	ela	*Atuna elata*
85	LS	Bei	dic	*Beilschmiedia dictyoneura*
86	LS	Bhe	pan	*Bhesa paniculata*
87	LS	Cal	dep	*Calophyllum depressinervosum*
88	LS	Can	ape	*Canarium apertum*
89	LS	Can	gra	*Canarium grandifolium*
90	LS	Car	bra	*Carallia brachiata*
91	LS	Cry	gri	*Crypteronia griffithii*
92	LS	Dac	cos	*Dacryodes costata*
93	LS	Dac	inc	*Dacryodes incurvata*
94	LS	Dac	rub	*Dacryodes rubigunosa*
95	LS	Dia	NK	Fam. *Leguminosae*
96	LS	Dia	mai	*Dialium maingayi*
97	LS	Dia	wal	*Dialium wallichii*
98	LS	Dil	gra	*Dillenia grandiflora*
99	LS	Dil	ret	*Dillenia reticulata*
100	LS	Dip	tem	*Dipterocarpus tempehes*
101	LS	Dra	dao	*Dracontomelon dao*
102	LS	Dry	rap	*Dryobalanops rappa*
103	LS	Dur	dul	*Durio dulcis*
104	LS	Dur	gra	*Durio graveolens*
105	LS	Dur	lan	*Durio lanceolatus*
106	LS	Dys	all	*Dysoxylum alliaceum*
107	LS	Dys	exc	*Dysoxylum excelsum*
108	LS	Ela	flo	*Elaeocarpus floribundus*

109	LS	End	kin	*Endiandra kingiana*
110	LS	Eug	gar	*Eugenia garcinifolia*
111	LS	Eug	koo	*Eugenia koordersiana*
112	LS	Eug	nap	*Eugenia napiformis*
113	LS	Eug	rug	*Eugenia rugosa*
114	LS	Eus	zwa	*Eusideraxylon zwageri*
115	LS	Fag	gig	*Fagraea gigantea*
116	LS	Glu	mal	*Gluta malayana*
117	LS	Glu	ren	*Gluta renghas*
118	LS	Glu	wal	*Gluta wallichii*
119	LS	Gym	ban	*Gymnacranthera bancana*
120	LS	Her	ela	*Heritiera elata*
121	LS	Hop	bec	*Hopea beccariana*
122	LS	Hop	men	*Hopea mengerawan*
123	LS	Irv	mal	*Irvingia malayana*
124	LS	Kok	ref	*Kokoona reflexa*
125	LS	Koo	mal	*Koompassia malaccensis*
126	LS	Koo	pin	*Koompassia pinnatum*
127	LS	Lit	cas	*Litsea castanea*
128	LS	Lit	fir	*Litsea firma*
129	LS	Lop	pal	*Lophopetalum pallidum*
130	LS	Mas	pen	*Mastixia pentandra*
131	LS	Myr	mai	*Myristica maingayi*
132	LS	Nee	syn	*Neesia synandra*
133	LS	Nep	lap	*Nephelium lappaceum*
134	LS	Pal	cla	*Palaquium clarkeanum*
135	LS	Pal	obo	*Palaquium obovatum*
136	LS	Pal	ros	*Palaquium rostratum*
137	LS	Par	obl	*Parinari oblongifolia*
138	LS	Pay	mai	*Payena maingayi*
139	LS	Pit	spl	*Pithecellobium splendens*
140	LS	Pla	val	*Planchonia valida*
141	LS	Pod	ner	*Podocarpus neriifolius*
142	LS	San	lae	*Santiria laevigata*
143	LS	San	obl	*Santiria oblongifolia*
144	LS	Sho	das	*Shorea dasyphylla*
145	LS	Sho	mul	*Shorea multiflora*
146	LS	Sho	pal	*Shorea palembanica*
147	LS	Sin	cor	*Sindora coriacea*
148	LS	Sin	vel	*Sindora velutina*
149	LS	Sin	wal	*Sindora wallichii*
150	LS	Tet	gla	*Tetramerista glabra*
151	LS	Vat	obl	*Vatica oblongifolia*
152	LS	Vat	ras	*Vatica rassak*
153	LS	Vat	sar	*Vatica sarawakensis*
154	LS	Vat	umb	*Vatica umbonata*
155	LS	Xan	obs	*Xanthophyllum obscurum*
156	LS	Xan	sti	*Xanthophyllum stipitatum*
157	MS	Act	sph	*Actinodaphne sphaerocarpa*
158	MS	Agl	gan	*Aglaia ganggo*
159	MS	Agl	hum	*Aglaia humilis*
160	MS	Agl	mal	*Aglaia malaccensis*
161	MS	Ala	ebe	*Alangium ebenaceum*
162	MS	Ala	nob	*Alangium nobile*
163	MS	Alp	ell	*Alphonsea elliptica*
164	MS	Apo	bra	*Aporusa bracteosa*
165	MS	Apo	fal	*Aporusa falcifera*
166	MS	Apo	ner	*Aporusa nervosa*
167	MS	Aqu	bec	*Aquilaria beccariana*
168	MS	Art	ani	*Artocarpus anisophyllus*
169	MS	Art	dad	*Artocarpus dadah*
170	MS	Art	int	*Artocarpus integer*
171	MS	Art	lan	*Artocarpus lanceifolius*
172	MS	Art	nit	*Artocarpus nitidus*
173	MS	Bar	pen	*Barringtonia pendula*
174	MS	Bei	mad	*Beilschmiedia madang*
175	MS	Bei	pal	*Beilschmiedia palembanica*
176	MS	Blu	kur	*Blumeodendron kurzii*
177	MS	Bou	opp	*Bouea oppositifolia*
178	MS	Can	lit	*Canarium littorale*
179	MS	Che	mal	*Cheilosa malayana*
180	MS	Chi	cer	*Chisocheton ceramicus*
181	MS	Cin	jav	*Cinnamomum javanicum*
182	MS	Cry	fer	*Cryptocarya ferrea*
183	MS	Cry	grf	*Cryptocarya griffithiana*
184	MS	Dac	ros	*Dacryodes rostrata*
185	MS	Deh	cun	*Dehaasia cuneata*
186	MS	Deh	inc	*Dehaasia incrassata*
187	MS	Deh	pol	*Dehaasia polyneura*
188	MS	Dio	bor	*Diospyros borneensis*
189	MS	Dio	bux	*Diospyros buxifolia*
190	MS	Dio	pen	*Diospyros pendula*
191	MS	Dio	sum	*Diospyros sumatrana*
192	MS	Dri	lur	*Drimycarpus luridus*
193	MS	Dry	lon	*Drypetes longifolia*
194	MS	Dur	acu	*Durio acutifolius*
195	MS	Dur	exc	*Durio excelsus*
196	MS	Dur	gri	*Durio griffithii*
197	MS	End	rub	*Endiandra rubescens*
198	MS	Eug	syz	*Eugenia syzygioides*
199	MS	Eug	vir	*Eugenia virens*
200	MS	Gar	ner	*Garcinia nervosa*
201	MS	Gar	nig	*Garcinia nigrolineata*
202	MS	Gir	ner	*Gironniera nervosa*
203	MS	Gle	pen	*Glenniea penangensis*
204	MS	Gon	kei	*Gonystylus keithii*
205	MS	Heo	vel	*Heliciopsis velutina*
206	MS	Hop	dry	*Hopea dryobalanoides*
207	MS	Hor	suc	*Horsfieldia sucosa*
208	MS	Hyd	kun	*Hydnocarpus kunstleri*
209	MS	Hyd	woo	*Hydnocarpus woodii*
210	MS	Kne	cin	*Knema cineria*
211	MS	Kne	fur	*Knema furfuracea*
212	MS	Lit	ben	*Lithocarpus bennettii*
213	MS	Lit	cur	*Lithocarpus curtisii*
214	MS	Lit	mac	*Litsea machilifolia*
215	MS	Lit	nid	*Litsea nidularis*
216	MS	Lit	ras	*Lithocarpus rassa*
217	MS	Lit	wry	*Litsea wrayi*
218	MS	Mad	ser	*Madhuca sericea*
219	MS	Mal	mut	*Mallotus muticus*
220	MS	Man	gri	*Mangifera griffithii*
221	MS	Man	hav	*Mangifera havelandii*
222	MS	Mas	tri	*Mastixia trichotoma*
223	MS	Mel	ful	*Maelanochyla fulvinervis*
224	MS	Mem	lil	*Memecylon lilacinum*
225	MS	Mes	gra	*Mesua grandis*
226	MS	Nau	off	*Nauclea officinalis*
227	MS	Neo	kin	*Neoscortechinia kingii*
228	MS	Neo	nic	*Neoscortechinia nicobarica*
229	MS	Nep	cos	*Nephelium costatum*
230	MS	Nep	gla	*Nephelium glabrum*
231	MS	Nep	mai	*Nephelium maingayi*
232	MS	Nep	unc	*Nephelium uncinatum*
233	MS	Not	umb	*Nothaphoebe umbelliflora*
234	MS	Per	eur	*Pertusadina eurhyncha*
235	MS	Pho	gra	*Phoebe grandis*
236	MS	Pim	gri	*Pimelodendron griffithianum*
237	MS	Pol	gla	*Polyalthia glauca*
238	MS	Pol	lat	*Polyalthia lateriflora*
239	MS	Pte	coe	*Pternandra coerulescens*
240	MS	Pte	tub	*Pterocymbium tubulatum*
241	MS	Que	gem	*Quercus gemelliflora*
242	MS	Que	oid	*Quercus oidocarpa*

243	MS	Rei	cin	*Reinwardtiodendron cinerium*	310	US	Gon	mac	*Gonystylus macrophyllus*
244	MS	San	gri	*Santiria griffithii*	311	US	Gon	mai	*Gonystylus maingayi*
245	MS	San	koe	*Santiria koetjape*	312	US	Gym	NK	Fam. *Myristicaceae*
246	MS	San	rub	*Santiria rubiginosa*	313	US	Gym	eug	*Gymnacranthera eugeniifolia*
247	MS	Scl	wal	*Scleropirum wallichianum*	314	US	Gym	for	*Gymnacranthera forbesii*
248	MS	Sco	bor	*Scorodocarpus borneensis*	315	US	Hel	NK	Fam. *Proteaceae*
249	MS	Ste	cor	*Sterculia cordata*	316	US	Hop	NK	Fam. *Dipterocarpaceae*
250	MS	Str	elo	*Streblus elongatus*	317	US	Hor	NK	Fam. *Myristicaceae*
251	MS	Str	jav	*Streblus javanica*	318	US	Hor	gla	*Horsfieldia glabra*
252	MS	Wal	pin	*Walsura pinnata*	319	US	Hyd	NK	Fam. *Flacourtiaceae*
253	MS	Xan	amo	*Xanthophyllum amoenum*	320	US	Ile	NK	Fam. *Aquifoliaceae*
254	MS	Xan	gri	*Xanthophyllum griffithii*	321	US	Ile	mac	*Ilex macrophylla*
255	MS	Xyl	mag	*Xylopia magna*	322	US	Ixo	gra	*Ixora grandifolia*
256	MS	Xyl	mal	*Xylopia malayana*	323	US	Kib	NK	Fam. *Monimiaceae*
257	US	Acr	por	*Acronychia porteri*	324	US	Kne	NK	Fam. *Myristicaceae*
258	US	Adi	acu	*Adinandra acuminata*	325	US	Kne	sco	*Knema scortechinii*
259	US	Agl	NK	Fam. *Meliaceae*	326	US	Kne	sum	*Knema sumatrana*
260	US	Agl	exi	*Aglaia eximia*	327	US	Koi	NK	Fam. *Euphorbiaceae*
261	US	Agl	exs	*Aglaia exstipulata*	328	US	Lan	NK	Fam. *Meliaceae*
262	US	Agl	sim	*Aglaia simplicifolia*	329	US	Las	NK	Fam. --------
263	US	Alp	NK	Fam. *Annonaceae*	330	US	Lep	NK	Fam. *Sapindaceae*
264	US	Als	NK	Fam. *Lauraceae*	331	US	Lic	NK	Fam. *Chrysobalanaceae*
265	US	Als	cor	*Alseodaphne coriacea*	332	US	Lit	ere	*Litsea erectinervia*
266	US	Als	umb	*Alseodaphne umbelliflora*	333	US	Lop	NK	Fam. *Celastraceae*
267	US	Ana	NK	Fam. *Olacaceae*	334	US	Mad	NK	Fam. *Sapotaceae*
268	US	Apo	NK	Fam. *Euphorbiaceae*	335	US	Mad	kin	*Madhuca kingiana*
269	US	Bar	NK	Fam. *Lecythidaceaee*	336	US	Mad	pal	*Madhuca pallida*
270	US	Bei	NK	Fam. *Lauraceae*	337	US	Mag	las	*Magnolia lasia*
271	US	Bri	pos	*Bridelia postulata*	338	US	Mal	NK	Fam. *Euphorbiaceae*
272	US	Bro	NK	Fam. *Tiliaceae*	339	US	Man	NK	Fam. *Anacardiacea*
273	US	Cal	NK	Fam. *Guttiferae*	340	US	Man	sim	*Mangifera similis*
274	US	Cal	arb	*Callicarpa arborea*	341	US	Mas	NK	Fam. *Cornaceae*
275	US	Chi	NK	Fam. *Meliaceae*	342	US	Mas	cus	*Mastixia cuspidata*
276	US	Cle	NK	Fam. *Euphorbiaceae*	343	US	Mei	vir	*Meiogyne virgata*
277	US	Cra	coc	*Cratoxylum cochinchinense*	344	US	Mel	NK	Fam. *Anacardiacea*
278	US	Cro	NK	Fam. *Euphorbiaceae*	345	US	Mem	NK	Fam. *Melastomaceae*
279	US	Cry	NK	Fam. *Lauraceae*	346	US	Mes	NK	Fam. *Guttiferae*
280	US	Dac	NK	Fam. *Burseraceae*	347	US	Mez	NK	Fam. *Annonaceae*
281	US	Den	NK	Fam. *Urticaceae*	348	US	Mez	par	*Mezzettia parviflora*
282	US	Den	ner	*Dendrokingstonia nervosa*	349	US	Mon	NK	Fam. *Annonaceae*
283	US	Dil	NK	Fam. *Dilleniaceae*	350	US	Mon	eun	*Monocarpia euneura*
284	US	Dil	pul	*Dillenia pulchella*	351	US	Myr	NK	Fam. *Myristicaceae*
285	US	Dio	NK	Fam. *Ebenaceae*	352	US	Myr	vil	*Myristica villosa*
286	US	Dio	pil	*Diospyros pilosanthera*	353	US	NK	NK	unidentified trees
287	US	Dio	wal	*Diospyros wallichii*	354	US	Nag	wal	*Nageia wallichiana*
288	US	Dip	NK	Fam. *Dipterocarpaceae*	355	US	Nau	ofi	*Nauclea officinalis*
289	US	Dip	cor	*Dipterocarpus cornutus*	356	US	Nee	NK	Fam. *Bombacaceae*
290	US	Dip	grc	*Dipterocarpus gracilis*	357	US	Neo	NK	Fam. *Euphorbiaceae*
291	US	Dry	NK	Fam. *Dipterocarpaceae*	358	US	Och	ame	*Ochanostachys amentacea*
292	US	Dry	pol	*Drypetes polyneura*	359	US	Pal	NK	Fam. *Sapotaceae*
293	US	Dys	NK	Fam. *Meliaceae*	360	US	Par	NK	Fam. *Chysobalanaceae*
294	US	Ela	NK	Fam. *Elaeocarpaceae*	361	US	Per	NK	Fam. *Rubiaceae*
295	US	Ela	acr	*Elaeocarpus acronodia*	362	US	Pho	NK	Fam. *Lauraceae*
296	US	Ela	sti	*Elaeocarpus stipularis*	363	US	Pol	scl	*Polyalthia sclerophylla*
297	US	Ell	cur	*Ellipanthus curtisii*	364	US	Pop	fus	*Popowia fusca*
298	US	Eni	fus	*Enicosanthum fuscum*	365	US	Pra	lim	*Prainea limpato*
299	US	Eug	NK	Fam. *Myrtaceae*	366	US	Pru	NK	Fam. *Rosaceae*
300	US	Eug	cym	*Eugenia cymosa*	367	US	Pru	jav	*Prunus javanica*
301	US	Eug	dye	*Eugenia dyeriana*	368	US	Pte	NK	Fam. *Melastomaceae*
302	US	Eug	ino	*Eugenia inophylla*	369	US	Pte	azu	*Pternandra azurea*
303	US	Eug	pra	*Eugenia prainiana*	370	US	Pte	ech	*Pternandra echinata*
304	US	Fic	NK	Fam. *Moraceae*	371	US	Que	NK	Fam. *Fagaceae*
305	US	For	NK	Fam. -------	372	US	Rei	NK	Fam. *Meliaceae*
306	US	Gan	NK	Fam. *Sapotaceae*	373	US	Ryp	NK	Fam. *Flacourtiaceae*
307	US	Gar	NK	Fam. *Rubiaceae*	374	US	San	NK	Fam. *Meliaceae*
308	US	Gle	NK	Fam. *Sapindaceae*	375	US	Sar	div	*Sarcotheca diversifolia*
309	US	Gon	NK	Fam. *Thymeleaceae*	376	US	Sho	bra	*Shorea bracteolata*

377	US	Slo	NK	Fam. *Elaeocarpaceae*
378	US	Ste	NK	Fam. *Icacinaceae*
379	US	Str	NK	Fam. *Moraceae*
380	US	Sym	NK	Fam. *Symplocaceae*
381	US	Ter	sub	*Terminalia subspathulata*
382	US	Tim	NK	Fam. *Rubiaceae*
383	US	Tim	bor	*Timonius borneensis*
384	US	Tri	NK	Fam. *Burseraceae*
385	US	Trp	mal	*Trigonopleura malayana*
386	US	Vat	NK	Fam. *Dipterocarpaceae*
387	US	Xyl	NK	Fam. *Annonaceae*

Medium and small faster growing species (Group MeSF)

388	MF	Agl	arg	*Aglaia argentea*
389	MF	Ant	chi	*Anthocephalus chinensis*
390	MF	Art	sco	*Artocarpus scortechinii*
391	MF	Can	odo	*Cananga odorata*
392	MF	Cin	ine	*Cinnamomum iners*
393	MF	Cro	arg	*Croton argyratus*
394	MF	Deh	lon	*Dehaasia longipetiolata*
395	MF	Dry	kik	*Drypetes kikir*
396	MF	Dua	mol	*Duabanga moluccana*
397	MF	Eng	ser	*Engelhardtia serrata*
398	MF	Gar	par	*Garcinia parvifolia*
399	MF	Gre	ant	*Grewia antidesmaefolia*
400	MF	Hop	ner	*Hopea nervosa*
401	MF	Ixo	ret	*Ixonanthes reticulata*
402	MF	Lit	cos	*Litsea costalis*
403	MF	Lit	enc	*Lithocarpus encleisacarpus*
404	MF	Lit	ewy	*Lithocarpus ewyckii*
405	MF	Lit	myr	*Litsea myristicaefolia*
406	MF	Lit	wra	*Lithocarpus wrayi*
407	MF	Mac	con	*Macaranga conifera*
408	MF	Mac	hos	*Macaranga hosei*
409	MF	Myr	max	*Myristica maxima*
410	MF	Pay	acu	*Payena acuminata*
411	MF	Pay	luc	*Payena lucida*
412	MF	Pen	ade	*Pentace adenophora*
413	MF	San	tom	*Santiria tomentosa*
414	MF	Str	cey	*Strombosia ceylanica*
415	MF	Tar	cos	*Tarenna costata*
416	MF	Xyl	ell	*Xylopia elliptica*
417	SF	Act	ses	*Actinodaphne sesquipedalis*
418	SF	Art	low	*Artocarpus lowii*
419	SF	Blu	tok	*Blumeodendron tokbrai*
420	SF	Eug	mic	*Eugenia microcalyx*
421	SF	Gar	tub	*Gardenia tubifera*
422	SF	Kne	lau	*Knema laurina*
423	SF	Mac	gig	*Macaranga gigantea*
424	SF	Mac	hyp	*Macaranga hypoleuca*
425	SF	Mac	tri	*Macaranga triloba*

Small slower growing species (Group SmaS)

426	SS	Agl	cor	*Aglaia cordata*
427	SS	Agl	cuc	*Aglaia cucullata*
428	SS	Agl	oli	*Aglaia oligophylla*
429	SS	Aid	wal	*Aidia wallichiana*
430	SS	Als	nig	*Alseodaphne nigrescens*
431	SS	Als	ped	*Alseodaphne peduncularis*
432	SS	Ana	hep	*Anacolosa heptandra*
433	SS	Aph	sum	*Alphonsea sumatrana*
434	SS	Apo	aur	*Aporusa aurea*
435	SS	Apo	fru	*Aporusa frutescens*
436	SS	Apo	lun	*Aporusa lunata*
437	SS	Apo	miq	*Aporusa miqueliana*
438	SS	Arc	mic	*Archidendron microcarpum*
439	SS	Bac	gri	*Baccaurea griffithii*
440	SS	Bac	mac	*Baccaurea macrophylla*
441	SS	Bac	rac	*Baccaurea racemosa*
442	SS	Buc	arb	*Buchanania arborescens*
443	SS	Can	pil	*Canarium pilosum*
444	SS	Cas	cla	*Casearia clarkei*
445	SS	Cha	cas	*Chaetocarpus castanocarpus*
446	SS	Cle	myr	*Cleistanthus myrianthus*
447	SS	Cle	sum	*Cleistanthus sumatranus*
448	SS	Cro	lae	*Croton laevifolius*
449	SS	Cya	car	*Cyathocalyx carinatus*
450	SS	Dac	pub	*Dacryodes puberula*
451	SS	Dac	rug	*Dacryodes rugosa*
452	SS	Dim	mur	*Dimorphocalyx muricatus*
453	SS	Dip	mal	*Diplospora malaccensis*
454	SS	Eug	att	*Eugenia attenuata*
455	SS	Eug	den	*Eugenia densiflora*
456	SS	Eug	lep	*Eugenia leptostemon*
457	SS	Eug	lin	*Eugenia linocieroidea*
458	SS	Eug	pol	*Eugenia polita*
459	SS	Eug	spi	*Eugenia spicata*
460	SS	Fah	pen	*Fahrenheitia pendula*
461	SS	Gar	mal	*Garcinia malaccensis*
462	SS	Glo	hyp	*Glocidion hypoleucum*
463	SS	Glo	wal	*Glocidion wallichianum*
464	SS	Gom	ser	*Gomphia serrata*
465	SS	Gre	bla	*Grewia blattaefolia*
466	SS	Gre	fib	*Grewia fibrocarpa*
467	SS	Gui	ple	*Guioa pleuropteris*
468	SS	Hel	ser	*Helicia serrata*
469	SS	Kne	int	*Knema intermedia*
470	SS	Kne	lat	*Knema latericia*
471	SS	Kne	ste	*Knema stenophylla*
472	SS	Koi	lon	*Koilodepas longifolium*
473	SS	Koi	pec	*Koilodepas pectinatum*
474	SS	Lan	dom	*Lansium domesticum*
475	SS	Lic	spl	*Licania splendens*
476	SS	Lit	blu	*Lithocarpus blumeanus*
477	SS	Mac	low	*Macaranga lowii*
478	SS	Mac	tan	*Macaranga tanarius*
479	SS	Mal	pen	*Mallotus penangensis*
480	SS	Man	foe	*Mangifera foetida*
481	SS	Myr	ine	*Myristica iners*
482	SS	Pol	rum	*Polyalthia rumphii*
483	SS	Pol	sum	*Polyalthia sumatrana*
484	SS	Pty	cos	*Ptychopyxis costata*
485	SS	Ryp	fas	*Ryparosa fasciculata*
486	SS	Ryp	kos	*Ryparosa kostermansii*
487	SS	San	api	*Santiria apiculata*
488	SS	Ste	mal	*Stemonurus malaccensis*
489	SS	Ste	rub	*Sterculia rubiginosa*
490	SS	Tei	bog	*Teijsmanniodendron bogoriense*
491	SS	Trs	lae	*Trigonostemon laevigatus*

Appendix 3.6. List of species codes and names for each of final selected species groups for PT. INHUTANI I data

Large faster growing species (Group LF)

No.	Grp. code	Gns. code	Spec. code	Species name
1	LF	Als	ang	*Alstonia angustifolia*
2	LF	Ani	sp	*Anisoptera sp.*
3	LF	Aqu	mal	*Aquilaria malaccensis*
4	LF	Art	ela	*Artocarpus elasticus*
5	LF	Cal	ino	*Calophyllum inophyllum*
6	LF	Can	meg	*Canarium megalanthum*
7	LF	Dip	cau	*Dipterocarpus caudiferus*
8	LF	Dry	lan	*Dryobalanops lanceolatum*
9	LF	Her	jav	*Heritiera javanica*
10	LF	Her	sim	*Heritiera simplicifolia*
11	LF	Her	sum	*Heritiera sumatrana*
12	LF	Hop	men	*Hopea mengerawan*
13	LF	Lit	ell	*Litsea elliptica*
14	LF	Oct	sum	*Octomeles sumatrana*
15	LF	Par	mal	*Parashorea malaanonan*
16	LF	Pen	pol	*Pentace polyantha*
17	LF	Sca	mac	*Scaphium macropodum*
18	LF	Sho	con	*Shorea confusa*
19	LF	Sho	exe	*Shorea exelliptica*
20	LF	Sho	fag	*Shorea faguetiana*
21	LF	Sho	fal	*Shorea fallax*
22	LF	Sho	hop	*Shorea hopeifolia*
23	LF	Sho	joh	*Shorea johorensis*
24	LF	Sho	lae	*Shorea laevis*
25	LF	Sho	lam	*Shorea lamellata*
26	LF	Sho	lep	*Shorea leprosula*
27	LF	Sho	lon	*Shorea longisperma*
28	LF	Sho	macp	*Shorea macrophyla*
29	LF	Sho	mec	*Shorea mecistopteryx*
30	LF	Sho	och	*Shorea ochracea*
31	LF	Sho	ova	*Shorea ovalis*
32	LF	Sho	paa	*Shorea parvistipulata* (Ashton)
33	LF	Sho	paf	*Shorea parvifolia*
34	LF	Sho	pau	*Shorea pauciflora*
35	LF	Sho	pin	*Shorea pinanga*
36	LF	Sho	sem	*Shorea seminis*
37	LF	Sho	smi	*Shorea smithiana*
38	LF	Sho	sp	*Shorea sp.*
39	LF	Sho	sup	*Shorea superba*
40	LF	Sho	sym	*Shorea symingtonii*
41	LF	Sho	vir	*Shorea virescens*

Large slower growing species (Group LS)

42	LS	Aga	bor	*Agathis borneensis*
43	LS	Als	ins	*Alseodaphne insignis*
44	LS	Ani	cos	*Anisoptera costata*
45	LS	Ani	lae	*Anisoptera laevis*
46	LS	Art	kem	*Artocarpus kemando*
47	LS	Bhe	pan	*Bhesa paniculata*
48	LS	Cal	sp	*Calophyllum sp.*
49	LS	Cam	aur	*Camnosperma auriculatum*
50	LS	Coe	bor	*Coelostegia borneensis*
51	LS	Cot	mel	*Cotylelobium melanoxylon*
52	LS	Cot	sp	*Cotylelobium sp.*
53	LS	Dac	cos	*Dcryoides costata*
54	LS	Dia	pro	*Dialium procerum*
55	LS	Dia	wal	*Dialium wallichii*
56	LS	Dil	exc	*Dillenia excelsa*
57	LS	Dip	acu	*Dipterocarpus acutangulus*
58	LS	Dip	con	*Dipterocarpus confertus*
59	LS	Dip	cos	*Dipterocarpus costulatus*
60	LS	Dip	elo	*Dipterocarpus elongatus*
61	LS	Dip	fam	*Dipterocarpaceae*
62	LS	Dip	gla	*Dipterocarpus glabrigemmatus*
63	LS	Dip	grac	*Dipterocarpus gracilis*
64	LS	Dip	pac	*Dipterocarpus pachyphyllus*
65	LS	Dip	pal	*Dipterocarpus palembanicus*
66	LS	Dip	sp	*Dipterocarpus sp.*
67	LS	Dip	ste	*Dipterocarpus stellatus*
68	LS	Dip	tem	*Dipterocarpus tempehes*
69	LS	Dip	ver	*Dipterocarpus verrucosus*
70	LS	Dra	dao	*Dracontomelon dao*
71	LS	Dur	gra	*Durio graveolens*
72	LS	Dur	oxl	*Durio oxleyanus*
73	LS	Dys	all	*Dysoxylum alliaceum*
74	LS	Eus	zwa	*Eusideraxylon zwageri*
75	LS	Glu	ren	*Gluta renghas*
76	LS	Glu	wal	*Gluta wallichii*
77	LS	Her	sp	*Heritiera sp.*
78	LS	Hop	pac	*Hopea pachycarpa*
79	LS	Irv	mal	*Irvingia malayana*
80	LS	Kok	ref	*Kokoona reflexa*
81	LS	Koo	mal	*Koompassia malaccensis*
82	LS	Koo	pin	*Koompassia pinnatum*
83	LS	Man	mac	*Mangifera macrocarpa*
84	LS	Nep	cus	*Nephelium cuspidatum*
85	LS	Pal	fer	*Palaquium ferrugineum*
86	LS	Pal	ros	*Palaquium rostratum*
87	LS	Par	obl	*Parinari oblongifolia*
88	LS	Par	smy	*Parashorea smythiessi*
89	LS	Par	sp	*Parashorea sp.*
90	LS	Pte	jav	*Pterospermum javanicum*
91	LS	San	lae	*Santiria laevigata*
92	LS	Sho	aga	*Shorea aganii*
93	LS	Sho	alm	*Shorea almon*
94	LS	Sho	atr	*Shorea atrinervosa*
95	LS	Sho	bec	*Shorea beccariana*
96	LS	Sho	ina	*Shorea inappendiculata*
97	LS	Sho	max	*Shorea maxima*
98	LS	Sin	cor	*Sindora coriacea*
99	LS	Sin	sp	*Sindora sp.*
100	LS	Sin	vel	*Sindora velutina*
101	LS	Sin	wal	*Sindora wallichii*
102	LS	Tet	gla	*Tetramerista glabra*
103	LS	Vat	mic	*Vatica micrantha*
104	LS	Vat	nit	*Vatica nitens*
105	LS	Vat	obl	*Vatica oblongifolia*
106	LS	Vat	odo	*Vatica odorata*
107	LS	Vat	ras	*Vatica rassak*
108	LS	Vat	sar	*Vatica sarawakensis*
109	LS	Vat	umb	*Vatica umbonata*
110	LS	Vat	vin	*Vatica vinosa*

111	LS	Xan	obs	*Xanthophyllum obscurum*

Medium, small, and other slower growing species (Group MSUS)

112	MS	Als	elm	*Alseodaphne elmeri*
113	MS	Art	ani	*Artocarpus anisophyllus*
114	MS	Art	dad	*Artocarpus dadah*
115	MS	Art	int	*Artocarpus integer*
116	MS	Art	lan	*Artocarpus lanceifolius*
117	MS	Art	nit	*Artocarpus nitidus*
118	MS	Art	sp	*Artocarpus sp.*
119	MS	Bar	mac	*Barringtonia macrostachya*
120	MS	Bar	pen	*Barringtonia pendula*
121	MS	Bou	mac	*Bouea macrophylla*
122	MS	Bou	opp	*Bouea oppositifolia*
123	MS	Can	den	*Canarium denticulatum*
124	MS	Can	lit	*Canarium littorale*
125	MS	Cas	meg	*Castanopsis megacarpa*
126	MS	Dac	lax	*Dacryoides laxa*
127	MS	Dac	ros	*Dacryoides rostrata*
128	MS	Dil	sum	*Dillenia sumatrana*
129	MS	Dio	ban	*Diospyros bantamensis*
130	MS	Dio	bor	*Diospyros borneensis*
131	MS	Dio	cur	*Diospyros curranii*
132	MS	Dio	fer	*Diospyros ferruginea*
133	MS	Dio	fru	*Diospyros frutescens*
134	MS	Dra	cos	*Dracontomelon costatum*
135	MS	Dur	acu	*Durio acutifolius*
136	MS	Dur	kut	*Durio kutejensis*
137	MS	Dur	sp	*Durio sp.*
138	MS	Gar	ner	*Garcinia nervosa*
139	MS	Gir	ner	*Gironniera nervosa*
140	MS	Hop	fer	*Hopea ferruginea*
141	MS	Hop	san	*Hopea sangal*
142	MS	Hop	sp	*Hopea sp.*
143	MS	Hyd	woo	*Hydnocarpus woodii*
144	MS	Kne	cin	*Knema cineria*
145	MS	Kne	con	*Knema conferta*
146	MS	Kne	fur	*Knema furfuracea*
147	MS	Mad	mal	*Madhuca malaccensis*
148	MS	Mad	ser	*Maducha sericea*
149	MS	Mal	mut	*Mallotus muticus*
150	MS	Man	qua	*Mangifera quadrifida*
151	MS	Mel	elm	*Melanochyla elmeri*
152	MS	Nep	mai	*Nephelium maingayi*
153	MS	Pal	eri	*Palaquium eriocalix*
154	MS	Pal	gut	*Palaquium gutta*
155	MS	Pen	bor	*Pentace borneensis*
156	MS	Pol	lat	*Polyalthia lateriflora*
157	MS	San	gri	*Santiria griffithii*
158	MS	Sca	bor	*Scapium borneensis*
159	MS	Sem	het	*Semecarpus heterophyllus*
160	MS	Sho	ang	*Shorea angustifolia*
161	MS	Sho	lept	*Shorea leptoderma*
162	MS	Sho	scr	*Shorea scrobiculata*
163	MS	Ste	gra	*Stemonorus grandiflorus*
164	MS	Sym	fas	*Symplocos fasciculata*
165	MS	Vat	sp	*Vatica sp.*
166	MS	Xyl	mal	*Xylophia malayana*
167	SS	Agl	odo	*Aglaia odoratissima*
168	SS	Agl	pol	*Aglaia polyantha*
169	SS	Agl	sha	*Aglaia shaviana*
170	SS	Agl	tom	*Aglaia tomentosa*
171	SS	Agl	tri	*Aglaia trichostemon*
172	SS	Apo	gra	*Aporusa grandistipulata*
173	SS	Apo	lun	*Aporusa lunata*
174	SS	Apo	sub	*Aporusa subcaudata*
175	SS	Art	odo	*Artocarpus odoratissimus*
176	SS	Bac	sum	*Baccaurea sumatrana*
177	SS	Can	cau	*Canarium caudatum*
178	SS	Cep	bec	*Cepalomappa beccariana*
179	SS	Cep	mal	*Cepalomappa malloticarpa*
180	SS	Cha	cas	*Chaetocarpus castanocarpus*
181	SS	Cyn	ram	*Cynometra ramiflora*
182	SS	Dac	rug	*Dacryodes rugosa*
183	SS	Dio	den	*Diospyros densa*
184	SS	Dio	end	*Diospyros enderti*
185	SS	Dys	cyr	*Dysoxylum cyrtobotryum*
186	SS	Dys	pac	*Dysoxylum pachyrhache*
187	SS	Fah	pen	*Fahrenheitia pendula*
188	SS	Gom	ser	*Gomphia serrata*
189	SS	Gon	cal	*Gonystylus calophylloides*
190	SS	Gre	fib	*Grewia fibrocarpa*
191	SS	Hor	bra	*Horsfieldia brachiata*
192	SS	Hor	gra	*Horsfieldia grandis*
193	SS	Hor	mac	*Horsfieldia macilenta*
194	SS	Kne	elm	*Knema elmeri*
195	SS	Kne	lat	*Knema latericia*
196	SS	Lep	amo	*Lepisanthes amoena*
197	SS	Mac	low	*Macaranga lowii*
198	SS	Mac	pru	*Macaranga pruinosa*
199	SS	Mad	lan	*Madhuca lancifolia*
200	SS	Mad	min	*Madhuca mindanaensis*
201	SS	Mad	pub	*Madhuca pubicalix*
202	SS	Mal	pen	*Mallotus penangensis*
203	SS	Man	foe	*Mangifera foetida*
204	SS	Mes	bor	*Mesua borneensis*
205	SS	Myr	cin	*Myristica cinnamonea*
206	SS	Myr	ine	*Myristica iners*
207	SS	Pal	cal	*Palaquium calophyllum*
208	SS	Pal	das	*Palaquium dasyphyllum*
209	SS	Pol	rum	*Polyalthia rumphii*
210	SS	Pol	sum	*Polyalthia sumatrana*
211	SS	Sho	mact	*Shorea macroptera*
212	SS	Tei	gla	*Teijsmanniodendron glabrus*
213	SS	Tei	sim	*Teijsmanniodendron simplicifolium*
214	SS	Vat	alb	*Vatica albiformis*
215	US	Act	mal	*Actinodaphne malaccensis*
216	US	Act	sp	*Actinodaphne sp.*
217	US	Act	sp1	*Actinodaphne sp1*
218	US	Act	sp2	*Actinodaphne sp2*
219	US	Ade	bic	*Adenanthera bicolor*
220	US	Agl	exi	*Aglaia exima*
221	US	Agl	sap	*Aglaia sapindina*
222	US	Agl	sp	*Aglaia sp.*
223	US	Ala	sp	*Alangium sp.*
224	US	All	sp	*Allantospermum sp.*
225	US	Als	sp	*Alseodaphne sp.*
226	US	Als	sp2	*Alseodaphne sp2*
227	US	Als	sp3	*Alseodaphne sp3*
228	US	Amo	sp	*Amoora sp*
229	US	Ana	fam	*Anacardiaceae*
230	US	Ann	2	*Annonaceae 2*
231	US	Ann	3	*Annonaceae 3*
232	US	Ann	fam	*Annonaceae*
233	US	Ant	sp	*Anthocephalus sp.*
234	US	Apo	fam	*Apocynaceae*
235	US	Apo	sp	*Aporusa sp.*
236	US	Apo	sp1	*Aporusa sp1*
237	US	Apo	sp3	*Aporusa sp3*
238	US	Apo	sp4	*Aporusa sp4*
239	US	Apo	sp5	*Aporusa sp5*
240	US	Apo	sp6	*Aporusa sp6*
241	US	Apo	sp8	*Aporusa sp8*
242	US	Ard	sp	*Ardisia sp*
243	US	Ard	sp1	*Ardisia sp1*
244	US	Art	gla	*Artocarpus glaucus*
245	US	Art	sp1	*Artocarpus sp1*
246	US	Art	sp2	*Artocarpus sp2*

247	US	Atu	asp	*Atuna asperula*	318	US	Dye	cos	*Dyera costulata*
248	US	Atu	sp	*Atuna sp.*	319	US	Dye	sp	*Dyera sp*
249	US	Bac	def	*Baccaurea deflexa*	320	US	Dys	amo	*Dysoxylum amooroides*
250	US	Bac	sp	*Baccaurea sp*	321	US	Dys	sp	*Dysoxylum sp*
251	US	Bac	sp1	*Baccaurea sp1*	322	US	Dys	sp1	*Dysoxylum sp1*
252	US	Bac	sp2	*Baccaurea sp2*	323	US	Ebe	fam	*Ebenaceae*
253	US	Bac	sp3	*Baccaurea sp3*	324	US	Ela	fam	*Elaeocarpaceae*
254	US	Bac	sp5	*Baccaurea sp5*	325	US	Ela	sp	*Elaeocarpus sp*
255	US	Bar	sp	*Barringtonia sp*	326	US	Ela	sp1	*Elaeocarpus sp1*
256	US	Bar	sp3	*Barringtonia sp3*	327	US	Ela	sp2	*Elaeocarpus sp2*
257	US	Bei	arg	*Beilschmiedia argentea*	328	US	Ela	sp3	*Elaeocarpus sp3*
258	US	Bei	dyc	*Beilschmiedia dyctioneura*	329	US	Ela	sp4	*Elaeocarpus sp4*
259	US	Bei	gem	*Beilschmiedia gemmiflora*	330	US	Ela	sp5	*Elaeocarpus sp5*
260	US	Bei	gig	*Beilschmiedia gigantocarpa*	331	US	Ela	sp6	*Elaeocarpus sp6*
					332	US	Ela	sp8	*Elaeocarpus sp8*
261	US	Bei	sp	*Beilschmiedia sp*	333	US	Ela	sp9	*Elaeocarpus sp9*
262	US	Bei	sp1	*Beilschmiedia sp1*	334	US	Ela	sp11	*Elaeocarpus sp11*
263	US	Bei	sp3	*Beilschmiedia sp3*	335	US	Ela	sp12	*Elaeocarpus sp12*
264	US	Bei	wie	*Beilschmiedia wieringae*	336	US	Ela	tap	*Elateriospermum tapos*
265	US	Blu	sp	*Blumeodendron sp*	337	US	Elat	sp1	*Elateriospermum sp1*
266	US	Blu	sp1	*Blumeodendron sp1*	338	US	Eug	sp	*Eugenia sp*
267	US	Blu	tok	*Blumeodendron tokophylla*	339	US	Eug	sp1	*Eugenia sp1*
268	US	Buc	sp1	*Buchanania sp1*	340	US	Eug	sp4	*Eugenia sp4*
269	US	Bur	fam	*Burseraceae*	341	US	Eug	sp6	*Eugenia sp6*
270	US	Cal	ech	*Calophyllum echinatum*	342	US	Eug	sp7	*Eugenia sp7*
271	US	Cal	sp1	*Calophyllum sp1*	343	US	Eug	sp8	*Eugenia sp8*
272	US	Cal	sp4	*Calophyllum sp4*	344	US	Eug	sp9	*Eugenia sp9*
273	US	Can	apt	*Canarium apterum*	345	US	Eug	sp11	*Eugenia sp11*
274	US	Can	elm	*Canarium elmeri*	346	US	Eug	sp12	*Eugenia sp12*
275	US	Can	sp	*Canarium sp*	347	US	Eug	sp13	*Eugenia sp13*
276	US	Can	sp1	*Canarium sp1*	348	US	Eug	sp14	*Eugenia sp14*
277	US	Can	sp2	*Canarium sp2*	349	US	Eug	sp15	*Eugenia sp15*
278	US	Can	sp4	*Canarium sp4*	350	US	Eug	sp17	*Eugenia sp17*
279	US	Cel	1	*Celastraceae1*	351	US	Eug	sp19	*Eugenia sp19*
280	US	Cel	2	*Celastraceae2*	352	US	Eug	sp2	*Eugenia sp2*
281	US	Cel	4	*Celastraceae4*	353	US	Eug	sp20	*Eugenia sp20*
282	US	Cel	fam	*Celastraceae*	354	US	Eug	sp21	*Eugenia sp21*
283	US	Chi	sp1	*Chionanthus sp1*	355	US	Eug	sp22	*Eugenia sp22*
284	US	Chi	sp2	*Chionanthus sp2*	356	US	Eup	4	*Euphorbiaceae4*
285	US	Chr	sp1	*Chrysophyllum sp1*	357	US	Eup	5	*Euphorbiaceae5*
286	US	Chr	sp2	*Chrysophyllum sp2*	358	US	Eup	7	*Euphorbiaceae7*
287	US	Cle	lae	*Cleistanthus laevis*	359	US	Eup	13	*Euphorbiaceae13*
288	US	Cru	sp	*Crudia sp*	360	US	Eup	14	*Euphorbiaceae14*
289	US	Cya	mag	*Cyathocalyx magnificus*	361	US	Eup	15	*Euphorbiaceae15*
290	US	Cyn	sp	*Cynometra sp*	362	US	Eup	16	*Euphorbiaceae16*
291	US	Dac	rost	*Dacryodes rostrata*	363	US	Eup	18	*Euphorbiaceae18*
292	US	Dac	sp	*Dacryods sp*	364	US	Eup	19	*Euphorbiaceae19*
293	US	Dac	sp5	*Dacryodes sp5*	365	US	Eup	21	*Euphorbiaceae21*
294	US	Dac	sp6	*Dacryodes sp6*	366	US	Eup	fam	*Euphorbiaceae*
295	US	Deh	mic	*Dehasia microcephala*	367	US	Evo	sp	*Evodia sp*
296	US	Der	thy	*Derris thyrsiflora*	368	US	Fag	3	*Fagaceae3*
297	US	Dia	pla	*Dialium platysepalum*	369	US	Fag	10	*Fagaceae10*
298	US	Dia	sp	*Dialium sp*	370	US	Fag	12	*Fagaceae12*
299	US	Dil	sp1	*Dillenia sp1*	371	US	Fag	13	*Fagaceae13*
300	US	Dio	sp	*Diospyros sp*	372	US	Fag	19	*Fagaceae19*
301	US	Dio	sp1	*Diospyros sp1*	373	US	Fag	22	*Fagaceae22*
302	US	Dio	sp2	*Diospyros sp2*	374	US	Fag	fam	*Fagaceae*
303	US	Dio	sp5	*Diospyros sp5*	375	US	Fic	sp1	*Ficus sp1*
304	US	Dio	sp6	*Diospyros sp6*	376	US	Fla	1	*Flacourtiaceae1*
305	US	Dio	sp7	*Diospyros sp7*	377	US	Fla	fam	*Flacourtiaceae*
306	US	Dio	sp10	*Diospyros sp10*	378	US	For	sp	*Fordia sp*
307	US	Dio	sp11	*Diospyros sp11*	379	US	For	sp1	*Fordia sp1*
308	US	Dip	gra	*Dipterocarpus grandiflorus*	380	US	For	sp2	*Fordia sp2*
309	US	Dip	hum	*Dipterocarpus humeratus*	381	US	Fra	sp3	*Fregrea sp3*
310	US	Dra	sp1	*Dracontomelon sp1*	382	US	Gal	sp	*Galearia sp*
311	US	Dry	kik	*Drypetes kikir*	383	US	Gan	sp	*Ganua sp*
312	US	Dry	sp	*Drypetes sp*	384	US	Gar	ban	*Garcinia bancana*
313	US	Dry	sp2	*Drypetes sp2*	385	US	Gar	cel	*Garcinia celebica*
314	US	Dry	sp3	*Drypetes sp3*	386	US	Gar	dio	*Garcinia dioica*
315	US	Dry	sp5	*Drypetes sp5*	387	US	Gar	mot	*Garcinia motleyana*
316	US	Dry	sp7	*Drypetes sp7*	388	US	Gar	rig	*Garcinia rigida*
317	US	Dry	sub	*Drypetes subsymetrica*	389	US	Gar	sp	*Garcinia sp*

390	US	Gar	sp2	*Garcinia sp2*	461	US	Nau	sp	*Nauclea sp*
391	US	Gar	sp4	*Garcinia sp4*	462	US	Neo	sum	*Neochortechinia sumatrensis*
392	US	Gar	sp6	*Garcinia sp6*					
393	US	Gir	sp	*Gironniera sp*	463	US	Nep	mut	*Nephelium mutabile*
394	US	Gir	sp1	*Gironniera sp1*	464	US	Nep	sp	*Nephelium sp*
395	US	Gir	sp2	*Gironniera sp2*	465	US	Nep	sp1	*Nephelium sp1*
396	US	Glu	sp	*Gluta sp*	466	US	Nep	sp2	*Nephelium sp2*
397	US	Glu	sp2	*Gluta sp2*	467	US	Nep	sum	*Nephelium sumatranum*
398	US	Glu	sp3	*Gluta sp3*	468	US	Och	ame	*Ochanostachys amentacea*
399	US	Gon	mac	*Gonystylus macrophyllus*	469	US	Och	sp	*Ochanostachys sp*
400	US	Gon	sp	*Gonystylus sp*	470	US	Pal	sp	*Palaquium sp*
401	US	Gon	sp1	*Gonystylus sp1*	471	US	Par	can	*Parinari canariodes*
402	US	Gon	sp2	*Gonystylus sp2*	472	US	Par	mai	*Parishia maingayi*
403	US	Gon	sp3	*Gonystylus sp3*	473	US	Par	sin	*Parkia singularis*
404	US	Gon	sp4	*Gonystylus sp4*	474	US	Par	ven	*Parartocarpus venenosus*
405	US	Goni	mac	*Goniothalamus macrophyllus*	475	US	Part	sp	*Paratocarpus sp*
					476	US	Pay	sp	*Payena sp*
406	US	Gono	sp	*Gonocaryum sp*	477	US	Pay	sp1	*Payena sp1*
407	US	Gut	fam	*Guttiferae*	478	US	Pen	ade	*Pentace adenophora*
408	US	Gym	for	*Gymnacranthera forbesii*	479	US	Pen	sp2	*Pentace sp2*
409	US	Her	acu	*Heritiera acuminata*	480	US	Pen	sp3	*Pentace sp3*
410	US	Her	sp1	*Heritiera sp1*	481	US	Per	sp	*Pertusadina sp*
411	US	Her	sp2	*Heritiera sp2*	482	US	Pero	sp	*Perospermum sp*
412	US	Hor	sp3	*Horsfieldia sp3*	483	US	Pit	bul	*Pithecellobium bulbalinum*
413	US	Ica	fam	*Icacinaceae*	484	US	Pit	glo	*Pithecellobium globosum*
414	US	Kne	lati	*Knema latifolia*	485	US	Pol	fam	*Polygalaceae*
415	US	Kne	lau	*Knema laurina*	486	US	Pol	sp	*Polyalthia sp*
416	US	Kne	sp	*Knema sp*	487	US	Pol	sp1	*Polyalthia sp1*
417	US	Koi	sp	*Koilodepas sp*	488	US	Pol	sp2	*Polyalthia sp2*
418	US	Koi	sp1	*Koilodepas sp1*	489	US	Pol	sp5	*Polyalthia sp5*
419	US	Koi	sp2	*Koilodepas sp2*	490	US	Pol	sp6	*Polyalthia sp6*
420	US	Kok	och	*Kokoona ochracea*	491	US	Pol	sp8	*Polyalthia sp8*
421	US	Kok	sp	*Kokoona sp*	492	US	Pol	sp9	*Polyalthia sp9*
422	US	Koo	exc	*Koompassia excelsa*	493	US	Pom	pin	*Pometia pinnata*
423	US	Lau	1	*Lauraceae1*	494	US	Pom	sp	*Pometia sp*
424	US	Lau	3	*Lauraceae3*	495	US	Pte	sp	*Pternandra sp*
425	US	Lau	4	*Lauraceae4*	496	US	Pte	sp1	*Pternandra sp1*
426	US	Lau	5	*Lauraceae5*	497	US	Pte	sp4	*Pternandra sp4*
427	US	Lau	fam	*Lauraceae*	498	US	Que	sp	*Quercus sp*
428	US	Leg	1	*Leguminosae1*	499	US	Rha	2	*Rhamnaceae2*
429	US	Leg	2	*Leguminosae2*	500	US	Rha	3	*Rhamnaceae3*
430	US	Leg	fam	*Leguminosae*	501	US	Ros	5	*Rosaceae5*
431	US	Lep	sp	*Lepisanthes sp*	502	US	Ros	7	*Rosaceae7*
432	US	Lit	sp	*Lithocarpus sp*	503	US	Ros	fam	*Rosaceae*
433	US	Lop	sp	*Lophopetalum sp*	504	US	Rub	1	*Rubiaceae1*
434	US	Mac	sp	*Macaranga sp*	505	US	Rub	13	*Rubiaceae13*
435	US	Mad	mag	*Madhuca magnifica*	506	US	Rub	14	*Rubiaceae14*
436	US	Mad	ses	*Madhuca sessilis*	507	US	Rub	17	*Rubiaceae17*
437	US	Mad	sp	*Madhuca sp*	508	US	Rub	18	*Rubiaceae18*
438	US	Mad	sp2	*Madhuca sp2*	509	US	Rub	23	*Rubiaceae23*
439	US	Mad	sp3	*Madhuca sp3*	510	US	Rub	25	*Rubiaceae25*
440	US	Mag	can	*Magnolia candollii*	511	US	Rub	27	*Rubiaceae27*
441	US	Mam	mal	*Mammea malayana*	512	US	Rub	4	*Rubiaceae4*
442	US	Man	sp	*Mangifera sp*	513	US	Rub	fam	*Rubiaceae*
443	US	Man	sp2	*Mangifera sp2*	514	US	San	bor	*Sandoricum borneensis*
444	US	Man	sp4	*Mangifera sp4*	515	US	San	sp	*Santiria sp*
445	US	Mel	4	*Meliaceae4*	516	US	San	sp1	*Santiria sp1*
446	US	Mel	fam	*Meliaceae*	517	US	Sap	1	*Sapotaceae1*
447	US	Mel	sp	*Melanochyla sp*	518	US	Sap	4	*Sapotaceae4*
448	US	Mela	fam	*Melastomaceae*	519	US	Sap	fam	*Sapotaceae*
449	US	Mem	sp	*Memecylon sp*	520	US	Sar	sp	*Sarcotheca sp*
450	US	Mes	sp	*Mesua sp*	521	US	Sch	wal	*Schima wallichii*
451	US	Mes	sp1	*Mesua sp1*	522	US	Sem	sp	*Semecarpus sp*
452	US	Mez	lep	*Mezzetia leptopoda.*	523	US	Sho	sp1	*Shorea sp1*
453	US	Mez	sp2	*Mezzetia sp2*	524	US	Sin	sp1	*Sindora sp1*
454	US	Mez	umb	*Mezzetia umbellata.*	525	US	Sin	sp2	*Sindora sp2*
455	US	Myr	2	*Myrtaceae2*	526	US	Sin	sp3	*Sindora sp3*
456	US	Myr	3	*Myrtaceae3*	527	US	Sin	sp4	*Sindora sp4*
457	US	Myr	fam	*Myrtaceae*	528	US	Ste	api	*Stemonorus apicalus*
458	US	Myr	sp	*Myristica sp*	529	US	Ste	fam	*Sterculiaceae*
459	US	Myri	fam	*Myristicaceae*	530	US	Ste	sp	*Stemonorus sp*
460	US	NK	NK	unidentified trees	531	US	Ste	sp1	*Stemonorus sp1*

532	US	Swi	sp	*Swintonia sp*
533	US	Swi	sp1	*Swintonia sp1*
534	US	Swi	sp3	*Swintonia sp3*
535	US	Tei	sp	*Teijsmanneodendron sp*
536	US	Tei	sp1	*Teijsmanneodendron sp1*
537	US	Tet	sp	*Tetramerista sp*
538	US	The	1	*Theaceae1*
539	US	The	2	*Theaceae2*
540	US	Thy	2	*Thymelaceae2*
541	US	Til	fam	*Tiliaceae*
542	US	Ulm	fam	*Ulmaceae*
543	US	Uva	sp	*Uvaria sp*
544	US	Uva	sp1	*Uvaria sp1*
545	US	Vat	sp1	*Vatica sp1*
546	US	Xan	aff	*Xanthophyllum affine*
547	US	Xan	sp	*Xanthophyllum sp*
548	US	Xan	sp1	*Xanthophyllum sp1*
549	US	Xan	sp3	*Xanthophyllum sp3*
550	US	Xan	sp5	*Xanthophyllum sp5*
551	US	Xan	sp8	*Xanthophyllum sp8*
552	US	Xan	sp10	*Xanthophyllum sp10*
553	US	Xan	sp11	*Xanthophyllum sp11*
554	US	Xan	sp13	*Xanthophyllum sp13*
555	US	Xan	spi	*Xanthophyllum spititatum*
556	US	Xyl	fus	*Xylopia fusca.*
557	US	Ziz	sp	*Zizypus sp*

Medium and small faster growing species (MeSF)

558	MF	Als	obl	*Alseodaphne oblanceolata*
559	MF	Ant	chi	*Anthocephalus chinensis*
560	MF	Cal	alb	*Calophyllum alboramulum*
561	MF	Cro	arg	*Croton argyratus*
562	MF	Deh	tom	*Dehasia tomentosa*
563	MF	Dryo	sp	*Dryobalanops sp*
564	MF	Hop	bra	*Hopea bracteata*
565	MF	Hop	ner	*Hopea nervosa*
566	MF	Hop	sem	*Hopea semicuneata*
567	MF	Pay	acu	*Payena acuminata*
568	MF	Pen	dis	*Pentace discolor*
569	MF	San	tom	*Santiria tomentosa*
570	MF	Sho	pat	*Shorea patoiensis*
571	SF	Apo	nit	*Aporusa nitida*
572	SF	Buc	ins	*Buccanania insignis*
573	SF	Mac	gig	*Macaranga gigantea*
574	SF	Mac	hyp	*Macaranga hypoleuca*
575	SF	Mac	tri	*Macaranga triloba*
576	SF	Que	sub	*Quercus subsericea*

Other faster growing species (Group UF)

577	UF	Adi	bor	*Adinandra borneensis*
578	UF	Als	dew	*Alseodaphne dewildei*
579	UF	Blu	sp2	*Blumeodendron sp2*
580	UF	Cal	aus	*Calophyllum austrocoriaceum*
581	UF	Cal	dep	*Calophyllum depressinervosum*
582	UF	Can	sp3	*Canarium sp3*
583	UF	Cas	sp	*Castanopsis sp*
584	UF	Cel	3	*Celastraceae3*
585	UF	Chi	div	*Chisocheton divergens*
586	UF	Cra	sp	*Cratoxyllon sp*
587	UF	Cry	ell	*Cryptocarya elliptica*
588	UF	Cry	sp1	*Cryptocarya sp1*
589	UF	Cya	sp	*Cyathocalyx sp*
590	UF	Dac	odo	*Dacriodes .....*
591	UF	Dac	pac	*Dacriodes pachyphyllus*
592	US	Deh	sp	*Dehasia sp*
593	US	Dia	ind	*Dialium indum*
594	US	Dil	sp	*Dillenia sp*
595	US	Dio	sp4	*Diospyros sp4*
596	US	Eug	sp3	*Eugenia sp3*
597	US	Eup	3	*Euphorbiaceae3*
598	US	Eup	17	*Euphorbiaceae17*
599	US	Fag	1	*Fagaceae1*
600	US	Fag	2	*Fagaceae2*
601	US	Fag	4	*Fagaceae4*
602	US	Fag	5	*Fagaceae5*
603	US	Fag	8	*Fagaceae8*
604	US	Fag	9	*Fagaceae9*
605	US	Fag	11	*Fagaceae11*
606	US	Fag	17	*Fagaceae17*
607	US	Fag	20	*Fagaceae20*
608	US	Fag	21	*Fagaceae21*
609	US	Fic	sp	*Ficus sp*
610	US	Gar	bai	*Garcinia bailloni*
611	US	Gre	cra	*Grewia crassifolia*
612	US	Hop	dry	*Hopea dryobalanoides*
613	US	Hor	sp	*Horsfieldia sp*
614	US	Hyd	sp1	*Hydnocarpus sp1*
615	US	Kne	sp1	*Knema sp1*
616	US	Lau	2	*Lauraceae2*
617	US	Lits	sp	*Litsea sp*
618	US	Mal	sp1	*Mallotus sp1*
619	US	Man	obl	*Mangifera oblongifolia*
620	US	Man	sp1	*Mangifera sp1*
621	US	Mem	sp2	*Memecylon sp2*
622	US	Mez	sp1	*Mezzetia sp1*
623	US	Pal	dub	*Pallaquium dubardii*
624	US	Par	sp1	---
625	US	Par	spe	*Parkia speciosa*
626	US	Pari	sp	*Parinari sp*
627	US	Park	sp	*Parkia sp*
628	US	Pen	sp	*Pentace sp*
629	US	Pen	sp1	*Pentace sp1*
630	US	Pter	sp	*Pterospermum sp*
631	US	Rub	3	*Rubiaceae3*
632	US	Rub	7	*Rubiaceae7*
633	US	Rub	9	*Rubiaceae9*
634	US	Rub	19	*Rubiaceae19*
635	US	Rub	28	*Rubiaceae28*
636	US	Sca	sp	*Scaphium sp*
637	US	Tri	obo	*Tristania obovata*
638	US	Tri	sp	*Tristania sp*
639	US	Xan	sp2	*Xanthophyllum sp2*
640	US	Xyl	sp	*Xylopia sp*

Appendix 3.7. Summary of PT. ITCI data for fitting Equations [7] and [8]

Selected group (+)	Species group	N_1	Mean d_1 (cm)	Mean d_i (cm/yr)	N_2 (RND>3.5)	N_3 (m.p.o.m)	N_4 (shrink)	N_5	N (total)
LFUF (4273)	LF	3194	41.38	0.67	135	117	26	4	4621
	UF	1280	28.38	0.65	66				
LMUS (8158)**	LS	3127	35.29	0.29	118	69	142	1	9859*
	MS	2291	26.40	0.28	90				
	US	4229*	28.15	0.30	118**				
MeSF (1364)	MF	1174	26.65	0.93	23	31	7	3	1437
	SF	222	23.73	0.85	9				
SmaS (1094)	SS	1130	22.39	0.21	36	2	25	3	1160

Note :

* including unidentified trees;

** excluding unidentified trees;

(+) selected species groups with number of observations used for predicting diameter increment (d_i) and future diameter (d_2) (excluding observations with RND > 3.5);

N_1 number of observations used for grouping species into faster and slower growing species (including observations with RND > 3.5);

N_2 number of observations with RND > 3.5;

N_3 number of observations with moving point of measurements (for tree diameter which were measured at different height between consecutive measurement because of buttresses/irregularities);

N_4 number of shrunk trees between consecutive measurements;

N_5 number of observations with diameter increment far removed from other observations (rejected);

N total number of observations ($\Sigma(N_1....N_5)$);

$\Sigma(N_1....N_4)$ used to calculate stand attributes.

Appendix 3.8. Summary of PT. INHUTANI I data

Selected group	Species group	N_1	Mean d_1 (cm)	Mean d_i (cm/yr)	N_2 (RND>3.5)	N_3	N_4 (shrink)	N_5	N (total)
LF	LF	4343	39.81	0.55	33	4310	209	6	4558
LS	LS	6140	33.20	0.36	56	6084	514	5	6659
UF	UF	1007	28.84	0.56	23	984	58	1	1066
MeSF	MF	389	26.80	0.62	13	530	24	6	589
	SF	170	25.69	0.66	18				
MSUS	MS	2859	25.37	0.29	31	16977**	438	8	21147*
	SS	1940	24.61	0.28	31				
	US	15902*	25.62	0.31	167**				

Note :

* including unidentified trees;

** excluding unidentified trees;

N_1 number of observations used for grouping species into faster and slower growing species (including observations with RND > 3.5);

N_2 number of observations with RND > 3.5;

N_3 number of observations used for predicting diameter increment (d_i) and future diameter (d_2) (excluding observations with RND > 3.5);

N_4 number of shrunk trees between consecutive measurements;

N_5 number of observations with diameter increment far removed from other observations (rejected);

N total number of observations ($\Sigma(N_1....N_5)$);

(N_1-N_4) used to calculate stand attributes.

Appendix 3.9. Summary of the combined PT. ITCI/PT. INHUTANI I data for four species groups

Species group	Source of data	$N^{(+)}$	Mean $d_1^{(+)}$ (cm)	Mean $d_i^{(+)}$ (cm/yr)	$N^{(++)}$	Mean $d_1^{(++)}$ (cm)	Mean $d_i^{(++)}$ (cm/yr)
DF	INH	3627	38.91	0.54	3649	39.01	0.56
DF	ITC	3191	39.59	0.60	3325	39.88	0.65
DS	INH	4683	32.87	0.34	4750	32.87	0.36
DS	ITC	890	28.13	0.29	947	28.46	0.32
NF	INH	1420	29.73	0.51	1467	29.52	0.60
NF	ITC	2271	27.87	0.75	2409	27.85	0.83
NS	INH	15331	25.47	0.27	18585*	25.59	0.31
NS	ITC	8352	28.61	0.24	9966	29.46	0.28

Appendix 3.10. Summary of the combined PT. ITCI/PT. INHUTANI I data for eight species groups

Species group	Source of data	$N^{(+)}$	Mean $d_1^{(+)}$ (cm)	Mean $d_i^{(+)}$ (cm/yr)	$N^{(++)}$	Mean $d_1^{(++)}$ (cm)	Mean $d_i^{(++)}$ (cm/yr)
LF	INH	3743	39.30	0.53	3767	39.40	0.55
LF	ITC	2948	41.23	0.62	3079	41.48	0.67
LS	INH	5212	33.00	0.33	5310	33.01	0.36
LS	ITC	2951	35.11	0.25	3120	35.31	0.29
MF	INH	318	26.68	0.56	331	26.30	0.73
MF	ITC	1093	26.45	0.88	1137	26.39	0.94
MS	INH	2534	25.39	0.27	2572	25.39	0.29
MS	ITC	2171	26.23	0.25	2271	26.42	0.28
SF	INH	143	26.45	0.44	155	25.85	0.61
SF	ITC	190	24.00	0.70	213	23.71	0.86
SS	INH	1712	24.30	0.25	1745	24.36	0.28
SS	ITC	1090	22.26	0.20	1130	22.39	0.21
UF	INH	847	28.46	0.54	863	28.41	0.59
UF	ITC	1248	28.21	0.58	1305	28.30	0.64
US	INH	10557	25.25	0.28	13708*	25.44	0.31
US	ITC	3034	26.17	0.24	4392	28.47	0.31

Appendix 3.11. Summary of the combined PT. ITCI/PT. INHUTANI I data for 10 species groups

Species group	Source of data	$N^{(+)}$	Mean $d_1^{(+)}$ (cm)	Mean $d_i^{(+)}$ (cm/yr)	$N^{(++)}$	Mean $d_1^{(++)}$ (cm)	Mean $d_i^{(++)}$ (cm/yr)
DF	INH	1801	39.20	0.53	1808	39.35	0.54
DF	ITC	1020	32.07	0.57	1057	32.57	0.62
DS	INH	3920	33.55	0.34	3944	33.55	0.36
DS	ITC	250	29.06	0.34	261	29.24	0.36
LF	INH	2219	37.12	0.54	2233	37.20	0.55
LF	ITC	2218	43.26	0.61	2299	43.50	0.65
LS	INH	1531	31.26	0.29	1581	31.35	0.34
LS	ITC	2147	37.01	0.25	2258	37.16	0.28
MF	INH	56	25.13	0.83	64	24.17	1.40
MF	ITC	454	26.55	0.92	457	26.51	0.94
MS	INH	1274	25.95	0.26	1291	25.97	0.28
MS	ITC	1046	24.58	0.24	1087	24.64	0.27
NF	INH	799	30.70	0.56	872	30.66	0.60
NF	ITC	1687	28.20	0.75	1759	28.13	0.81
NS	INH	12208	24.86	0.27	15910*	25.08	0.31
NS	ITC	5368	26.38	0.24	6978*	27.92	0.29
SF	INH	136	26.59	0.42	148	25.95	0.60
SF	ITC	143	23.18	0.76	162	22.77	0.95
SS	INH	589	24.10	0.25	600	24.29	0.28
SS	ITC	323	20.69	0.19	329	20.71	0.20

Note :

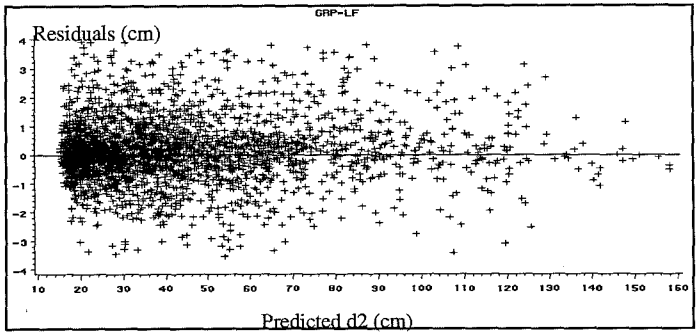
For Appendices 3.2.1.6a-c :

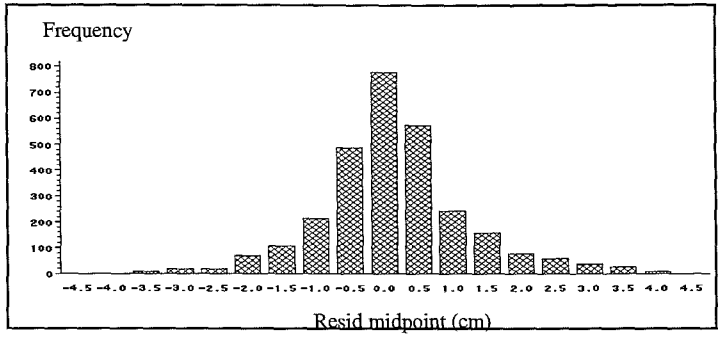
* including unidentified trees;

(+) number of observations used for predicting future diameter (excluding observations with RND > 3.5);

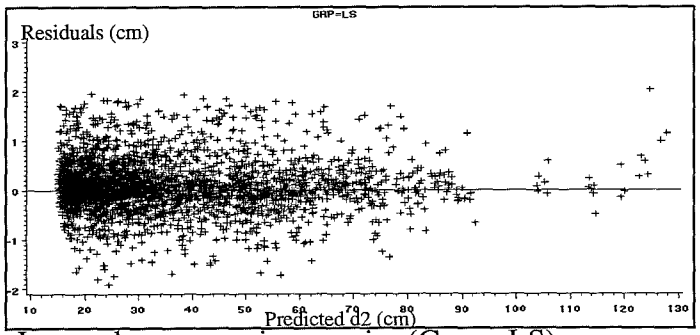
(++) including observations with RND > 3.5

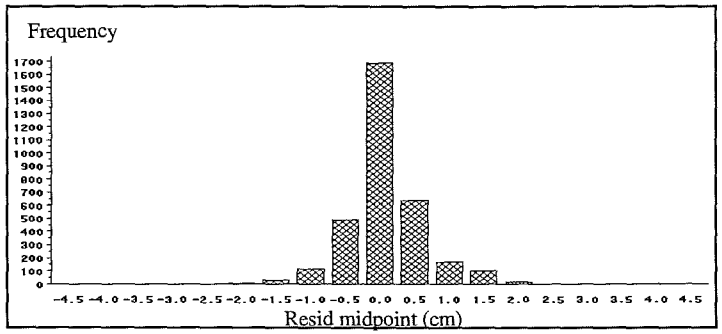
Appendix 4.6a. Residual patterns and distributions of a modified Gompertz projection form (Equation [7]) for 8 species groups of PT. ITCI data



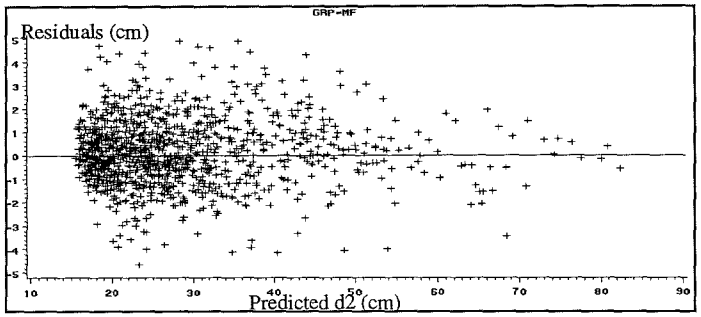


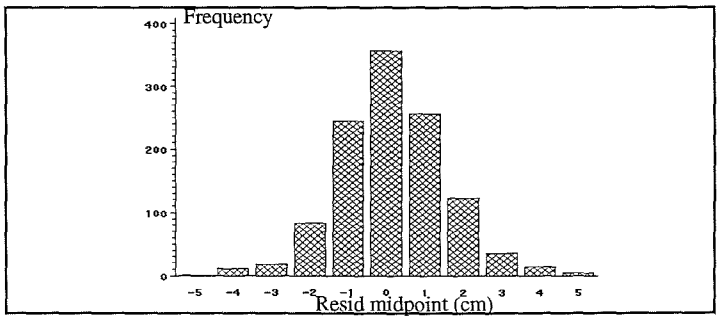
Large faster growing species (Group LF)



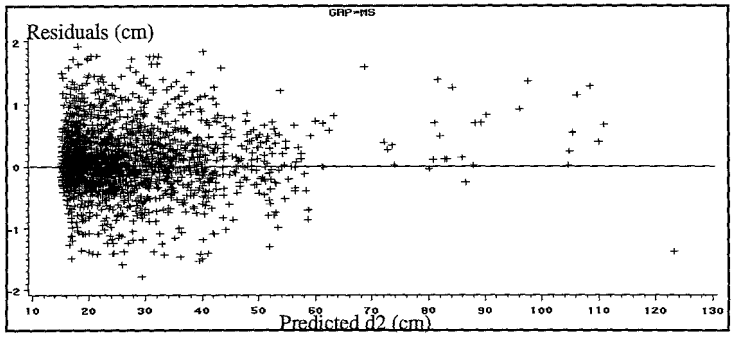


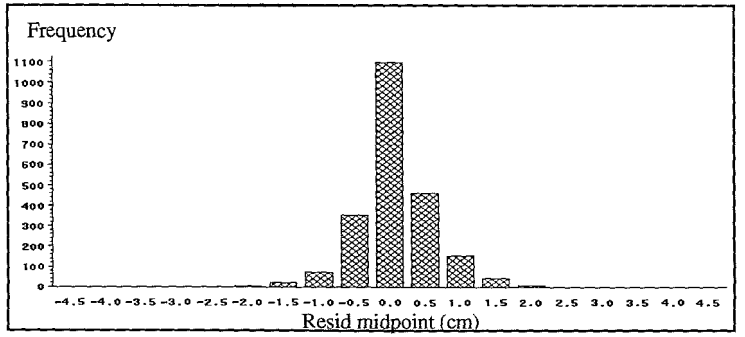
Large slower growing species (Group LS)



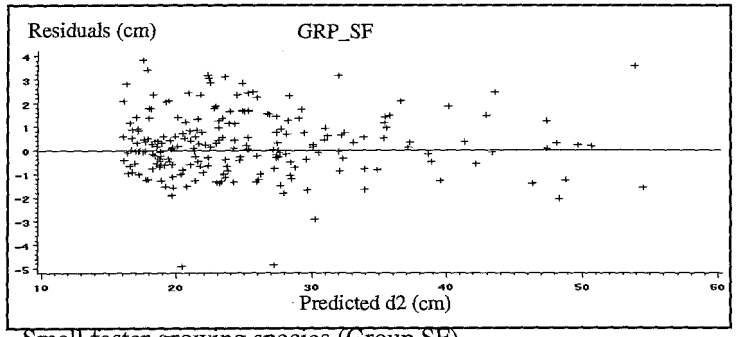


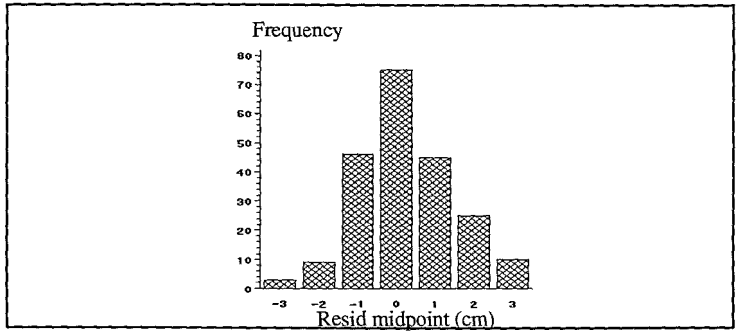
Medium faster growing species (Group MF)



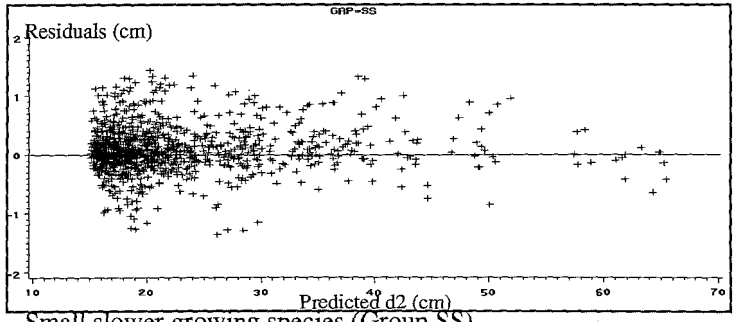


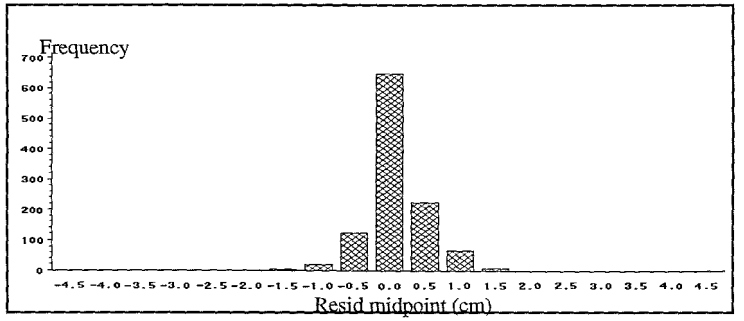
Medium slower growing species (Group MS)



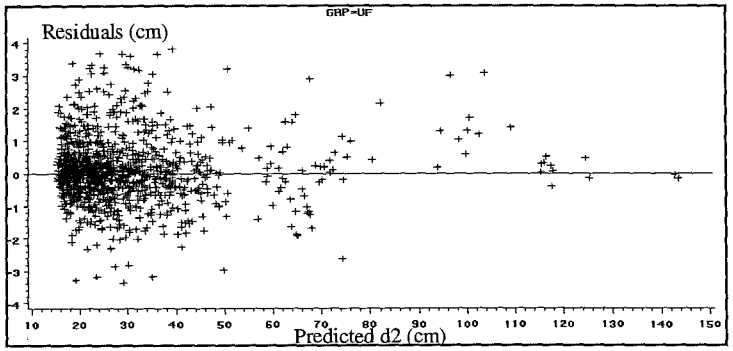


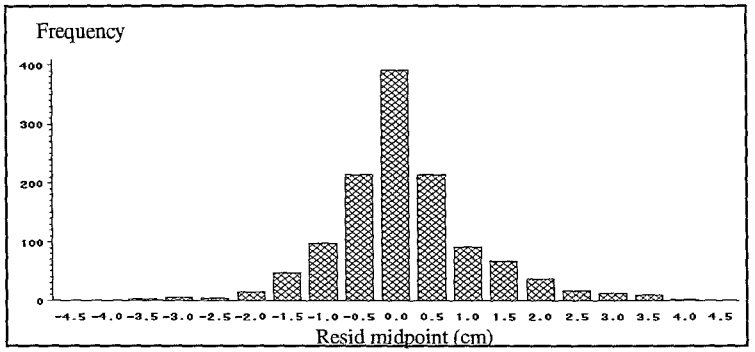
Small faster growing species (Group SF)



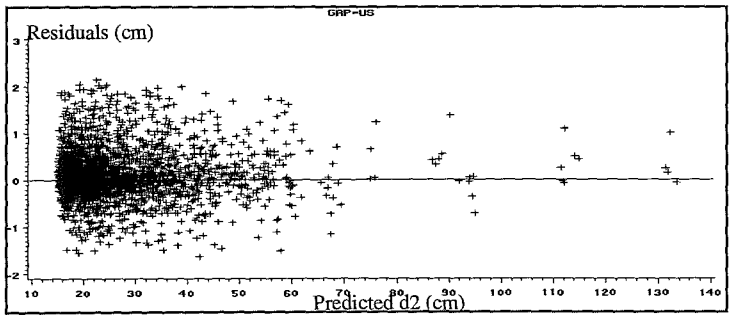


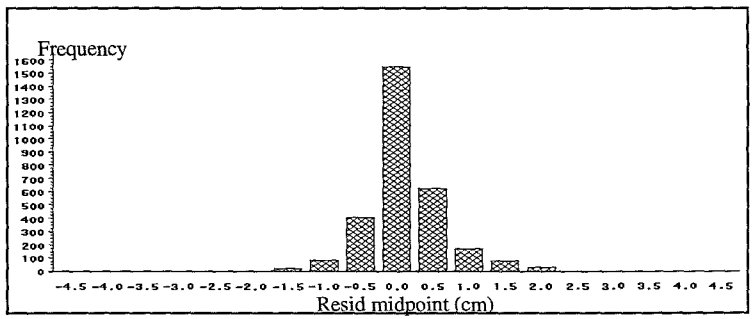
Small slower growing species (Group SS)





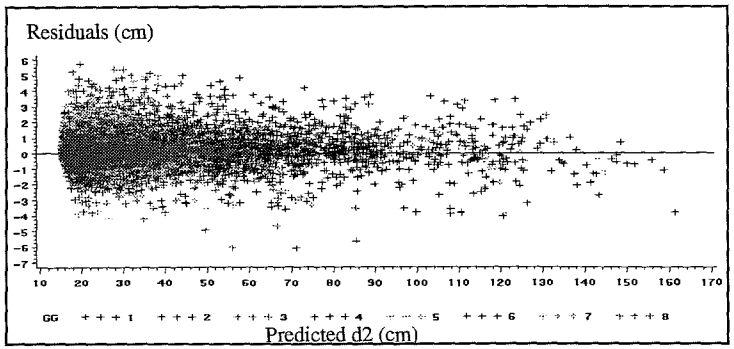
Other faster growing species (Group UF).

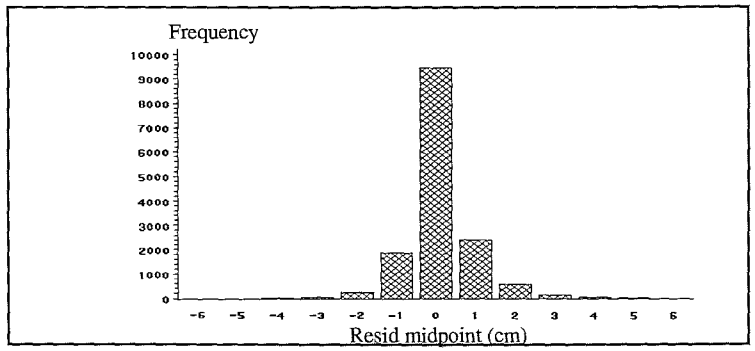




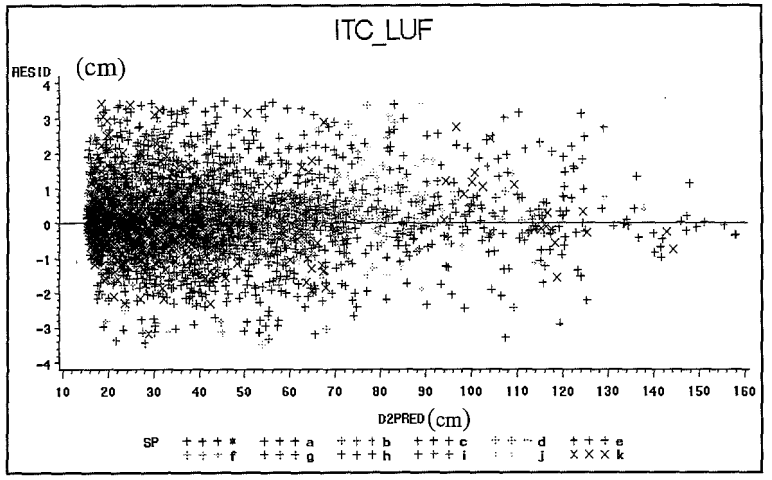
Other slower growing species (Group US)

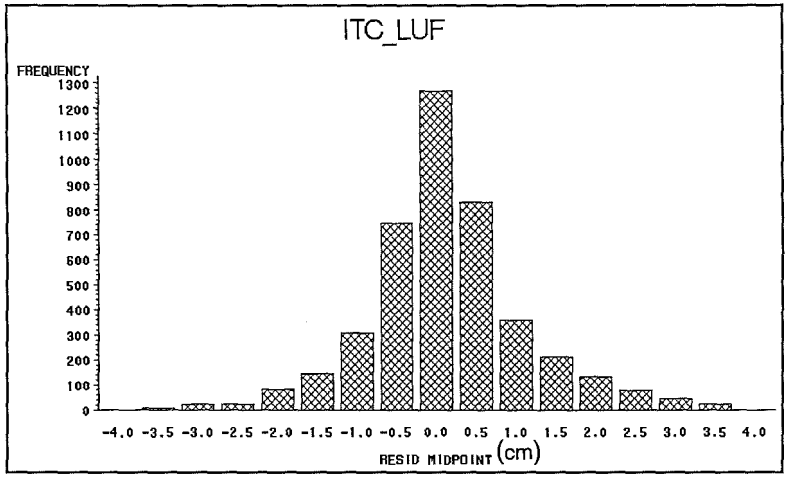
Appendix 4.7c. Residual patterns and distributions for all species/groups as dummy variable for PT. ITCI data, drawn from Eq. [7]



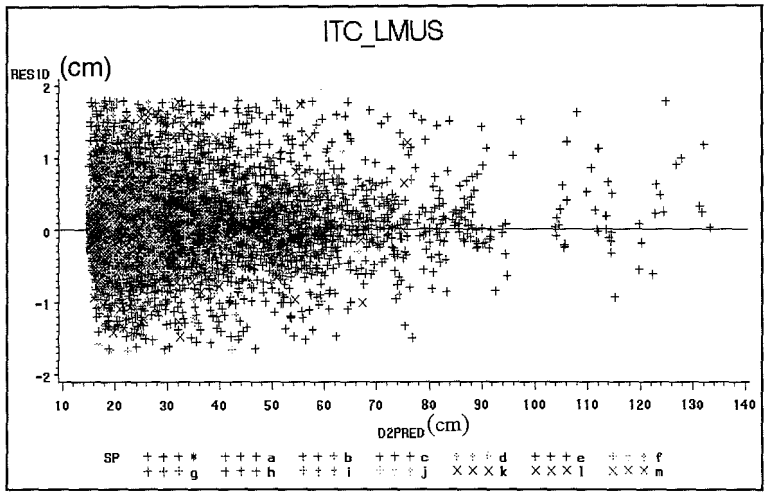


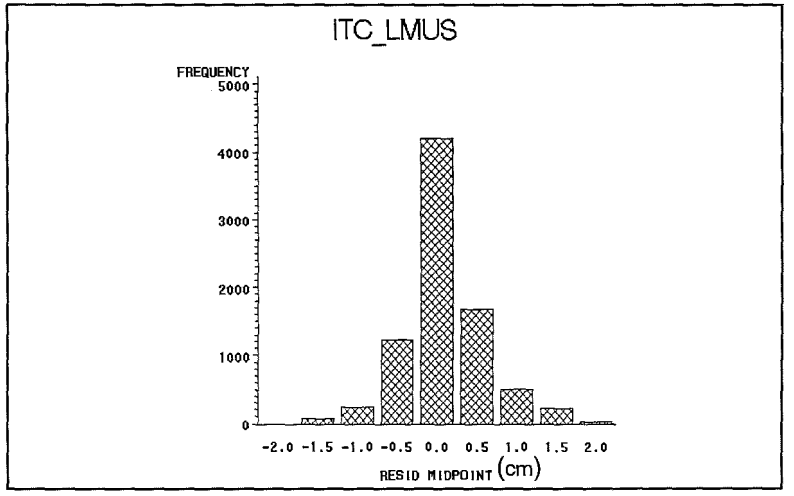
Appendix 4.9a. Residual patterns and distributions for four final selected species groups of PT. ITCI data, obtained from Equation [7]



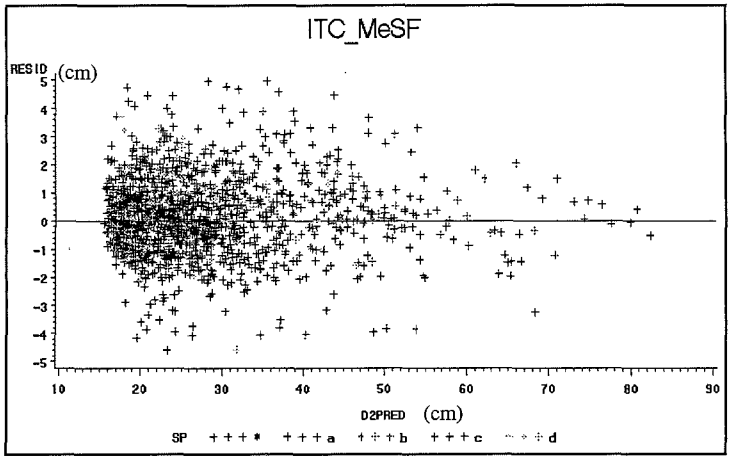


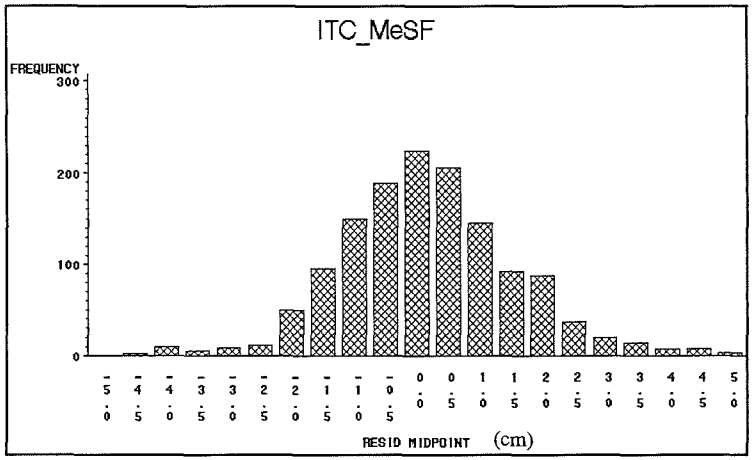
Large and other faster growing species (Group LUF)



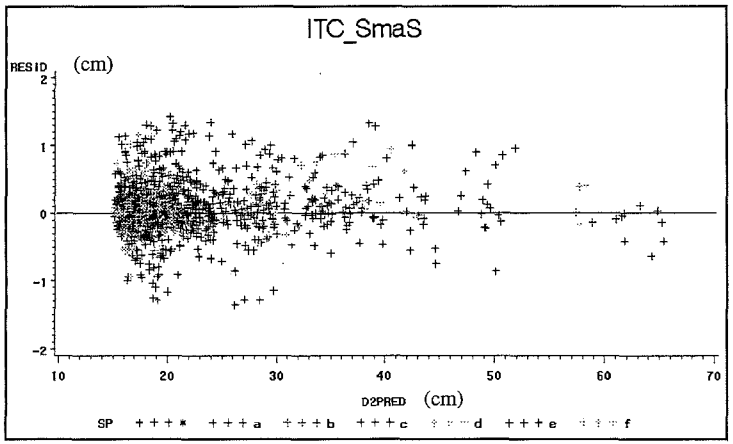


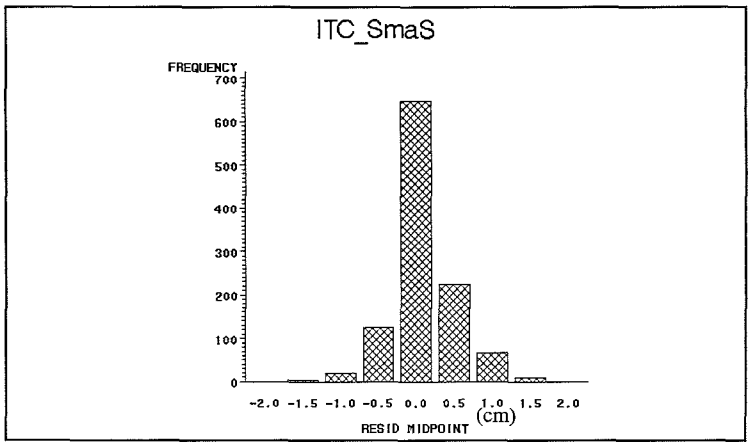
Large, medium, and other slower growing species (Group LMUS)





Medium and small faster growing species (Group MeSF)

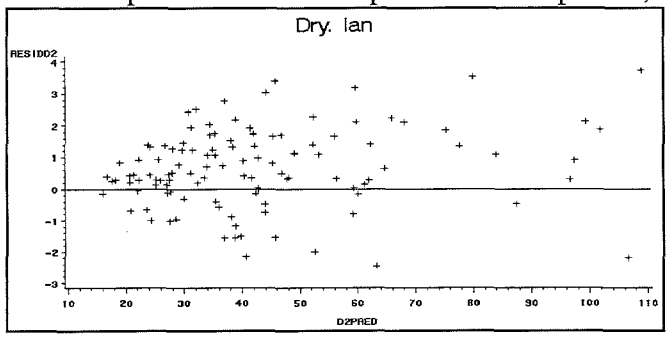




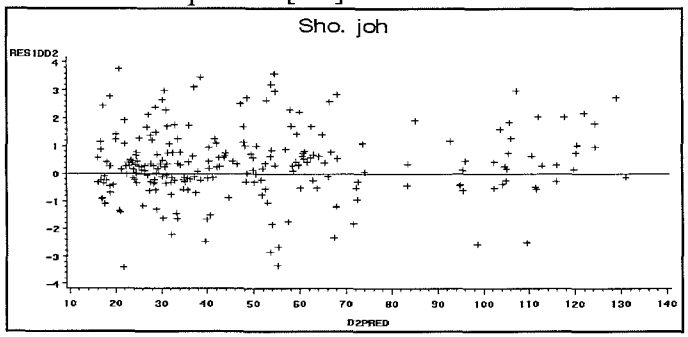
Small slower growing species (SmaS)]

Appendix 4.10. Plots of residuals against predicted values for individual species with many data for PT. ITCI

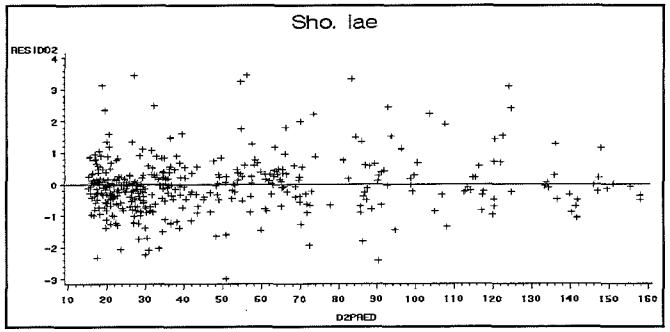
Residual patterns for some species of Group LUF, obtained from Equation [7.a]



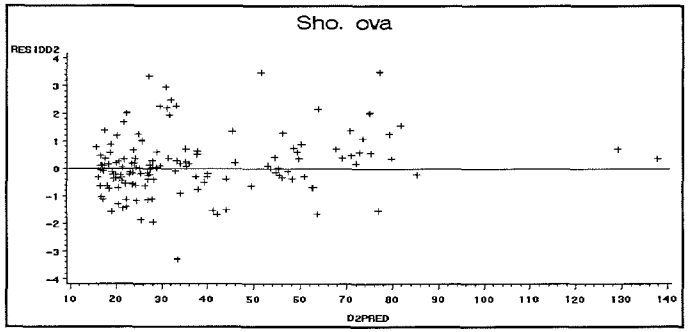
Dryobalanops lanceolata



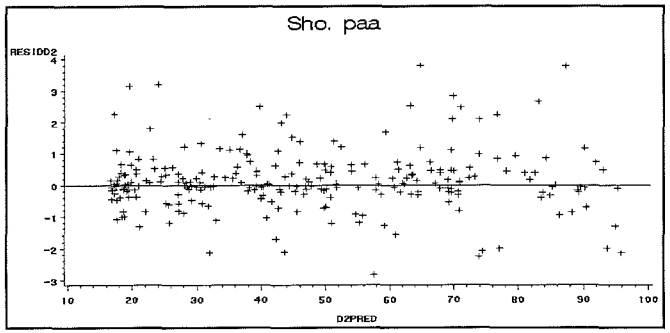
Shorea johorensis



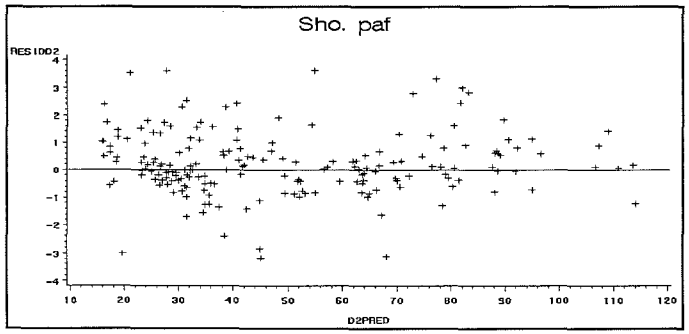
Shorea laevis



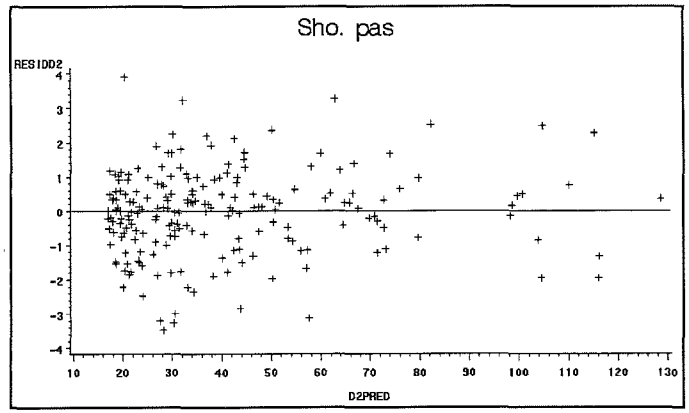
Shorea ovalis



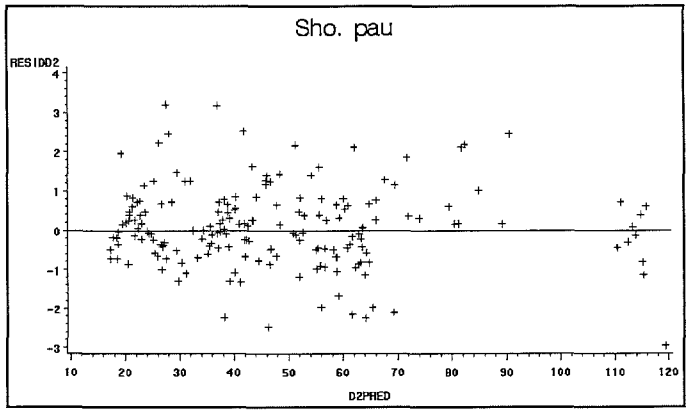
Shorea parvistipulata (Ashton)



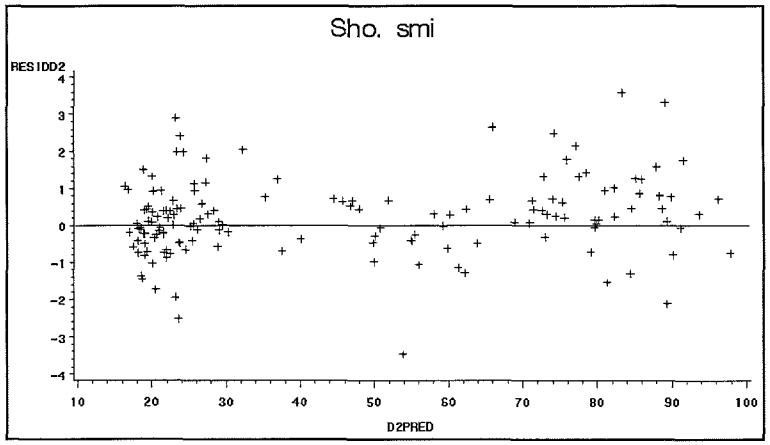
Shorea parvifolia



Shorea parvistipulata (Meijer)

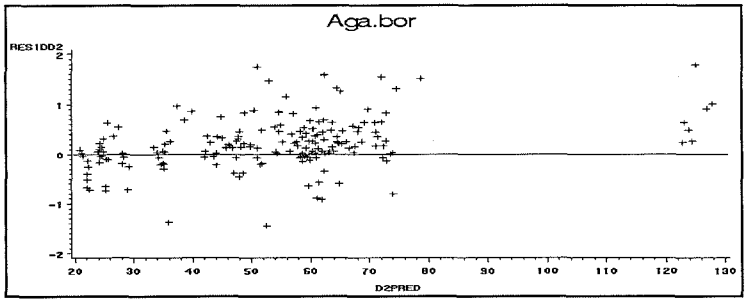


Shorea pauciflora

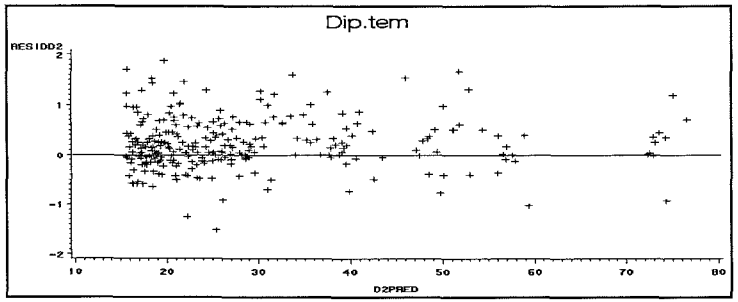


Shorea smithiana

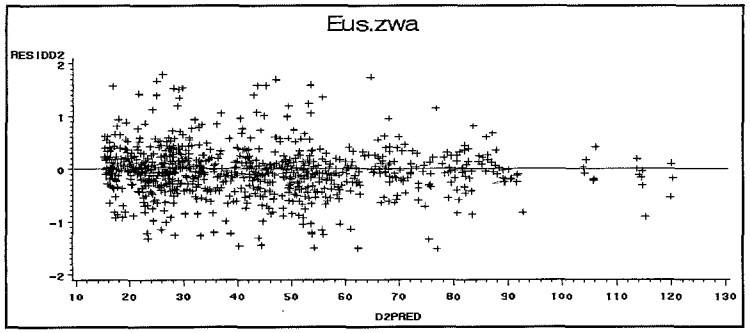
Residual patterns for some species of Group LMUS, obtained from Equation [7.b]



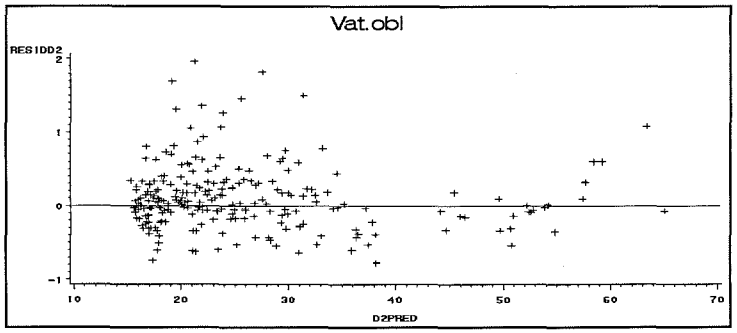
Agathis borneensis



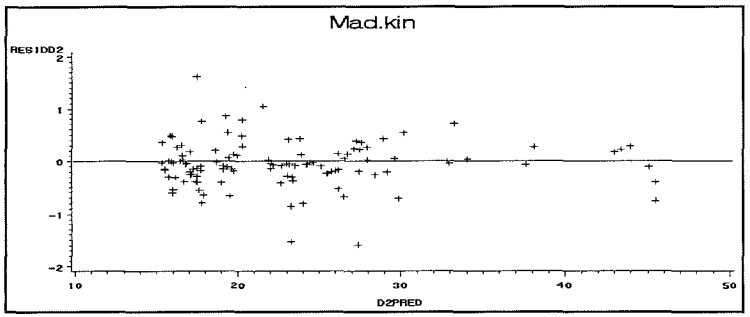
Dipterocarpus tempehes



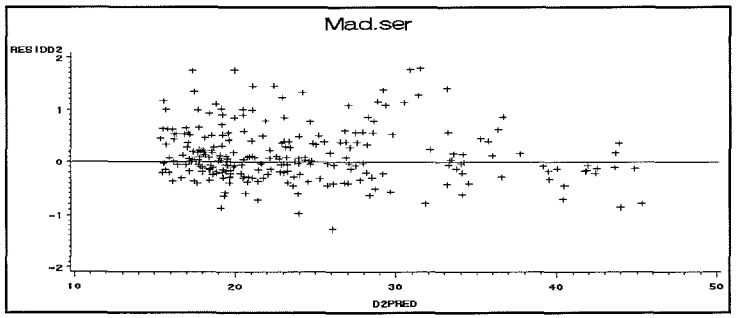
Eusideraxylon zwageri



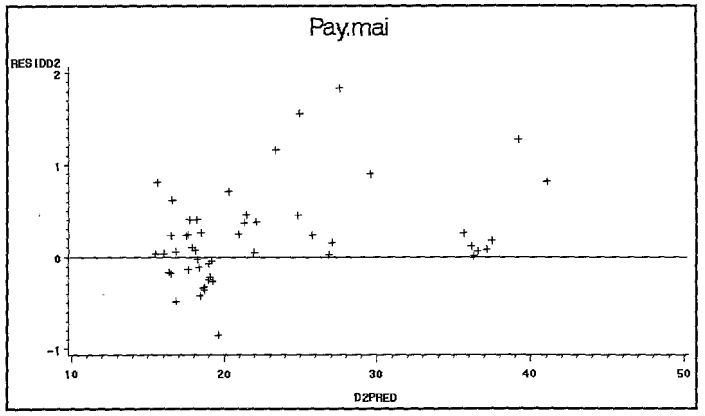
Vatica oblongifolia



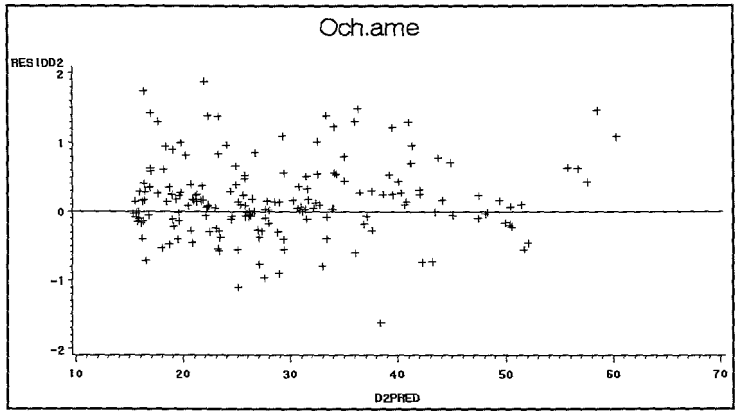
Madhuca kingiana



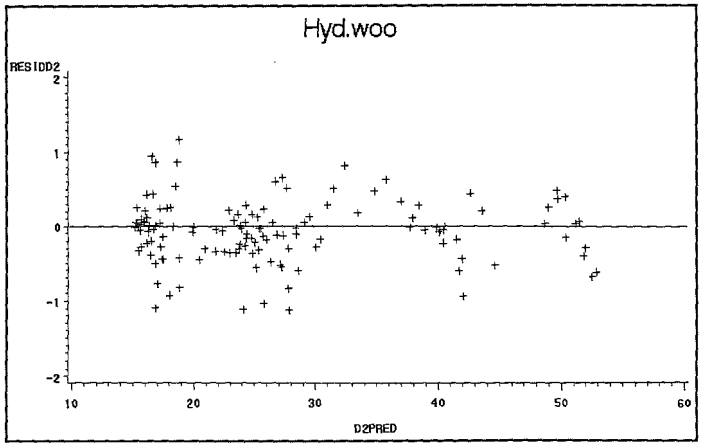
Madhuca sericea



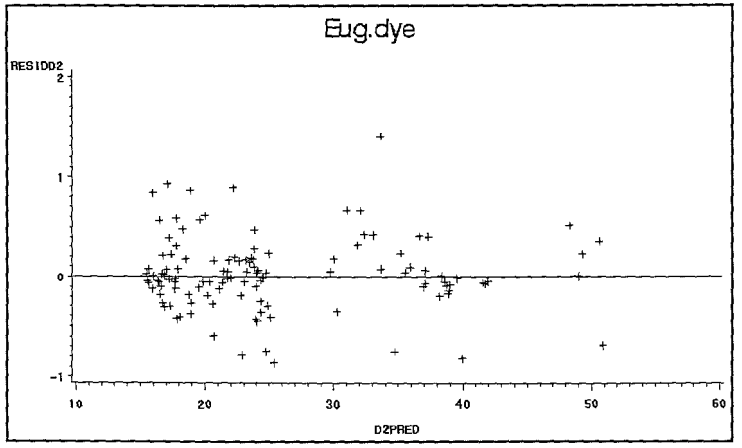
Payena maingayi



Ochanostachys amentacea

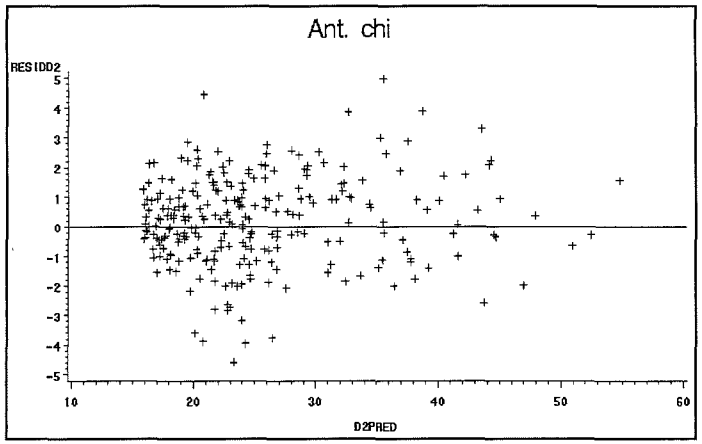


Hydnocarpus woodii

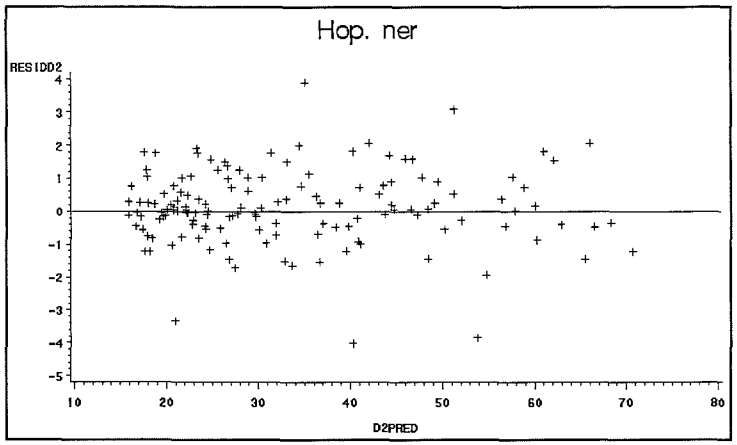


Eugenia dyeriana

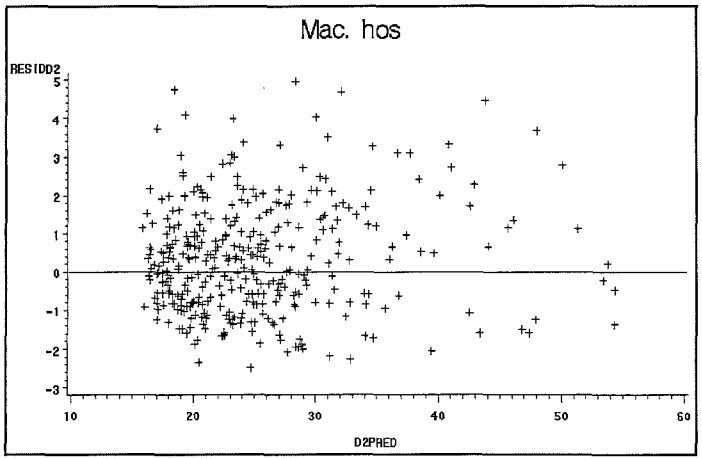
Residual patterns for some species of Group MeSF, obtained from Equation [7.c]



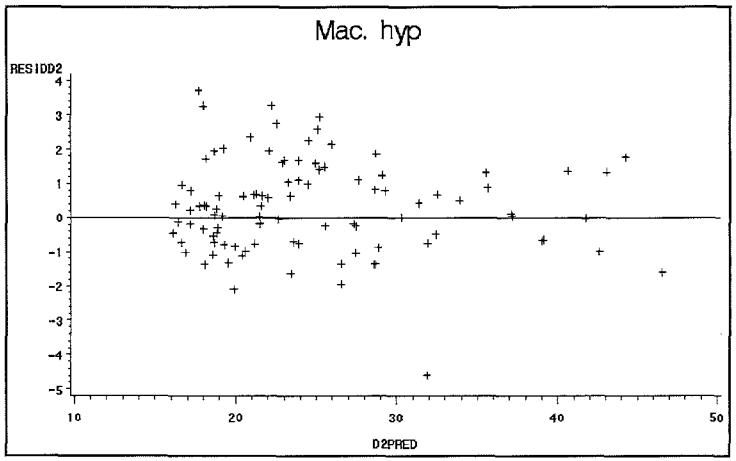
Anthocephalus chinensis



Hopea nervosa

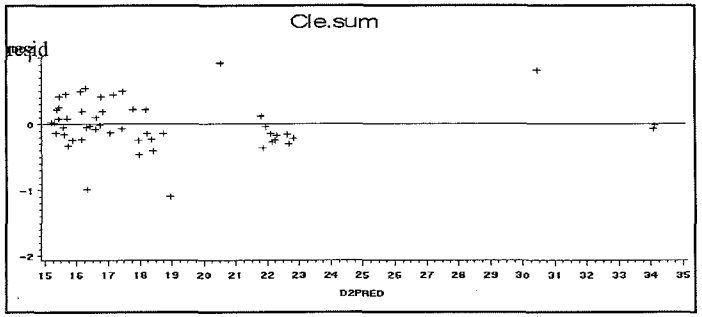


Macaranga hosei

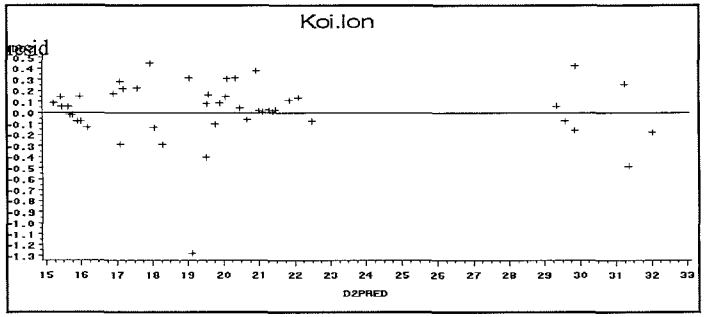


Macaranga hypoleuca

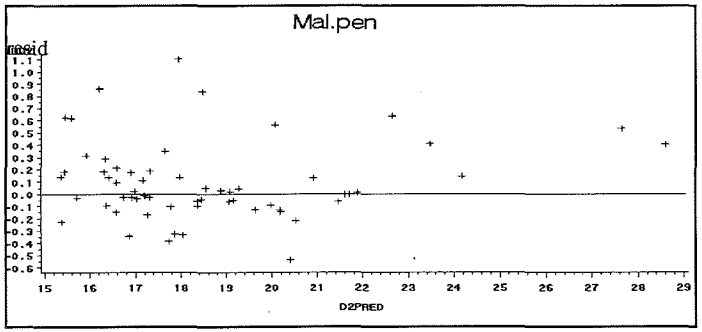
Residual patterns for some species of Group SmaS, obtained from Equation [7.d]



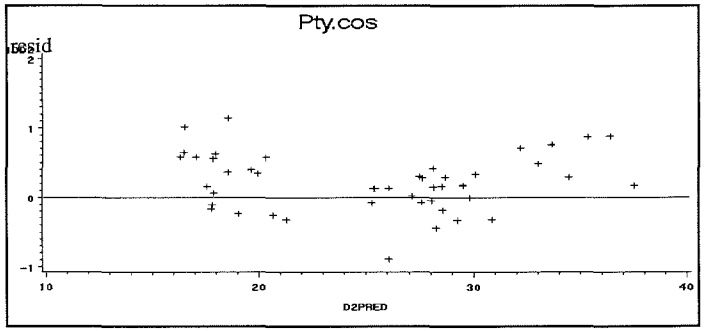
Cleistanthus sumatranus



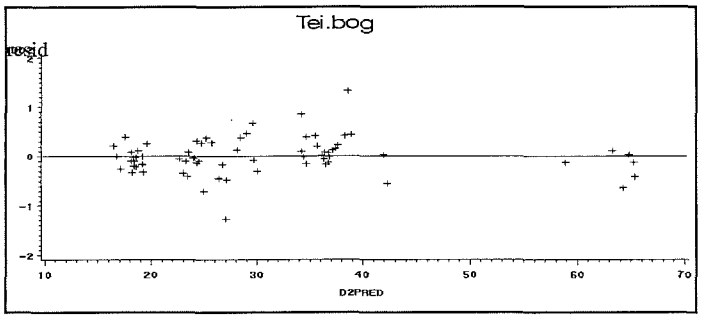
Koilodepas longifolium



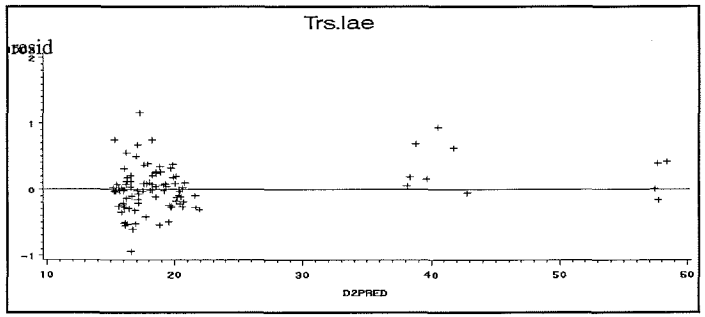
Mallotus penangensis



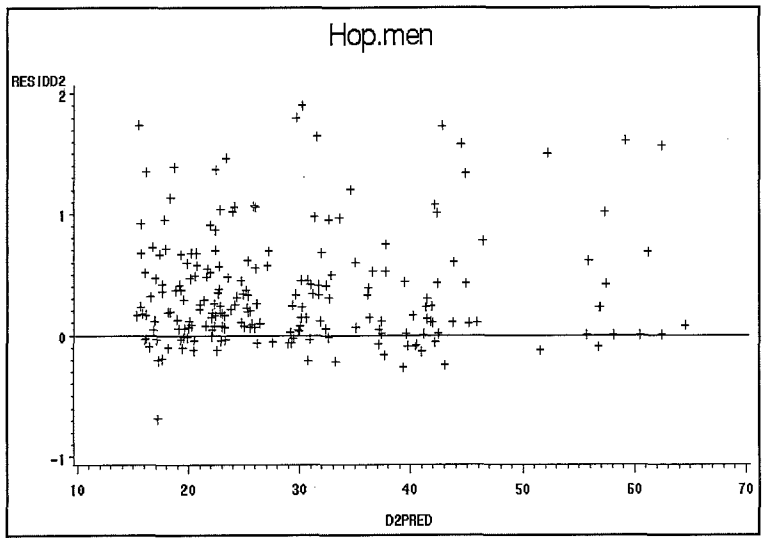
Ptychopyxis costata



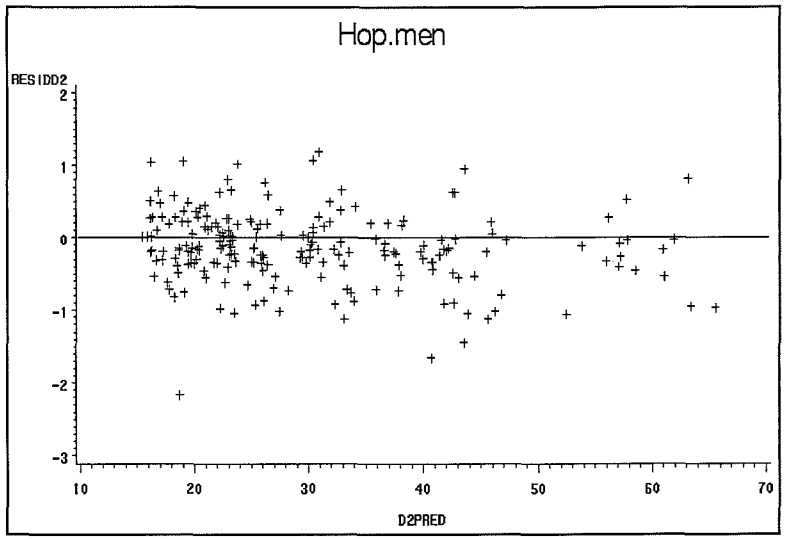
Teijsmanniodendron bogoriense



Trigonostemon laevigatus

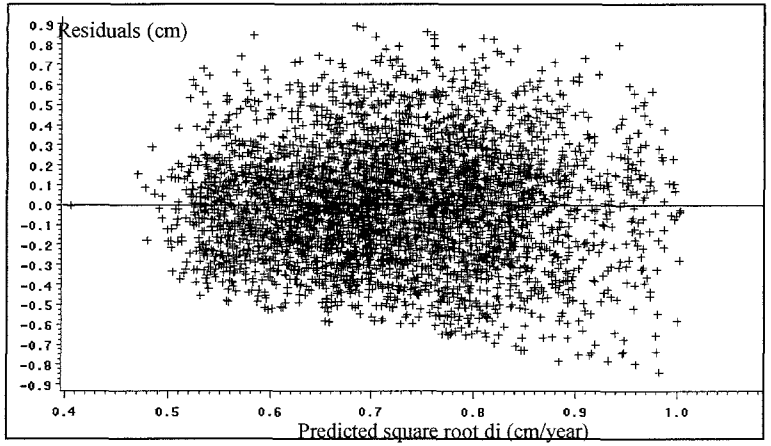


Appendix 4.11..Plot of residuals against predicted values (d2) for *Hopea mengerawan* using Group LMUS model (Equation [7.b])

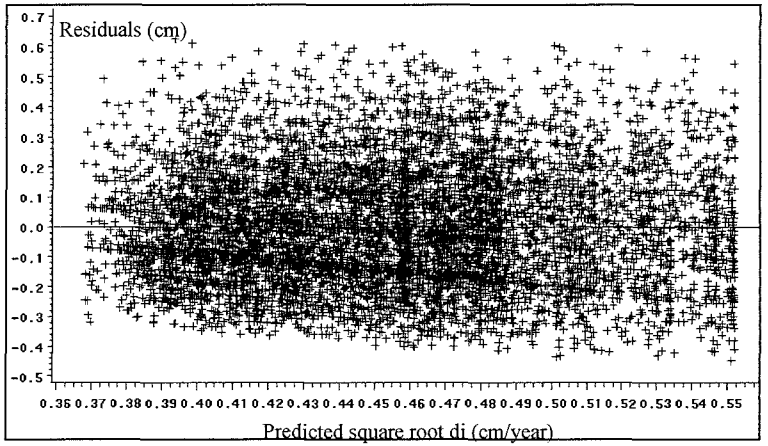


Appendix 4.12.. Plot of residuals against predicted values (d2) for *Hopea mengerawan* using GroupLUF model (Equation 7.a])

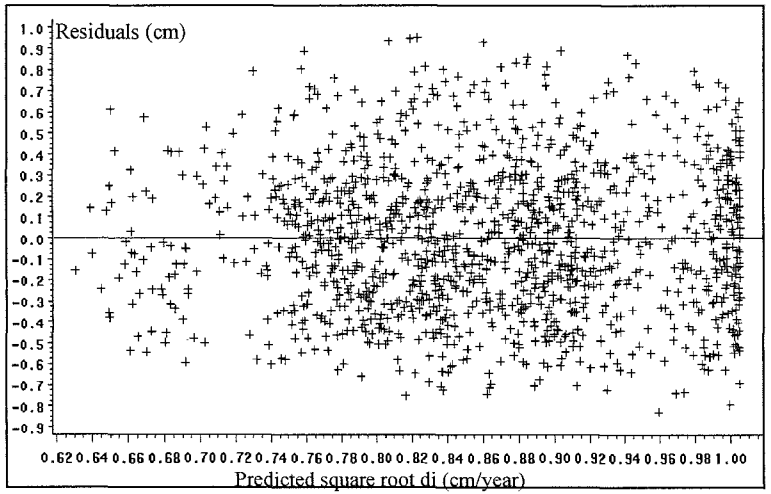
Appendix 4.13a. Residual patterns for four species groups of PT. ITCI data, drawn from Equations [8.a1-4]



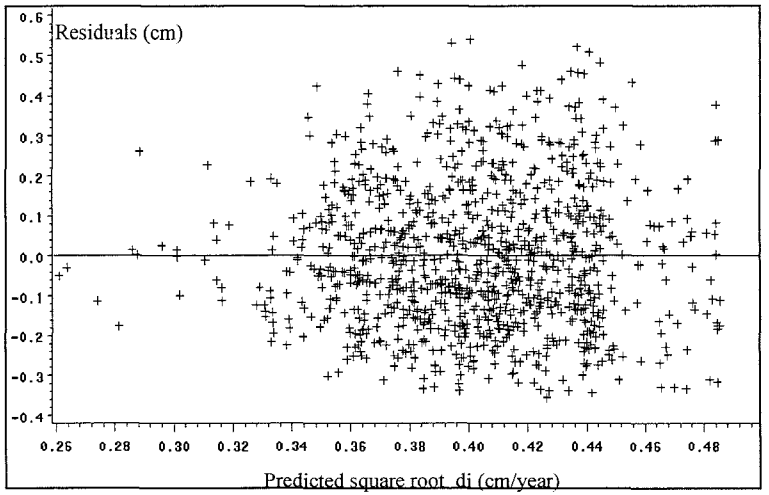
. Group LUF



. Group LMUS

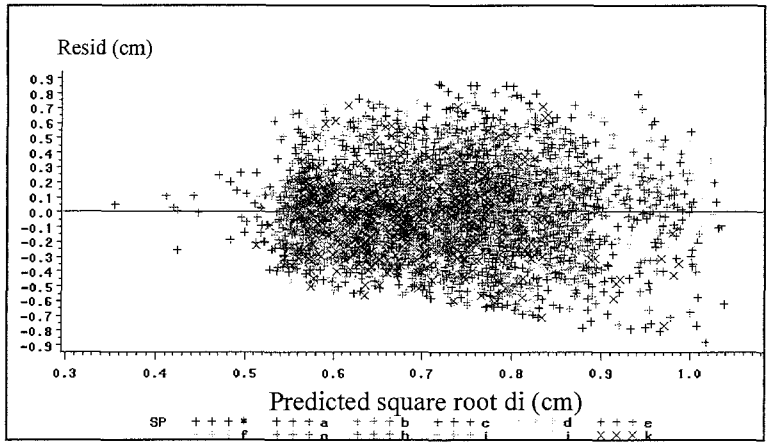


. Group MeSF

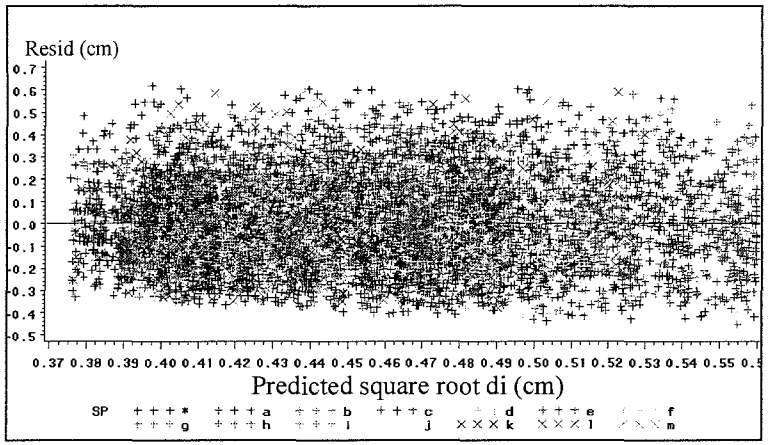


. GroupSmaS

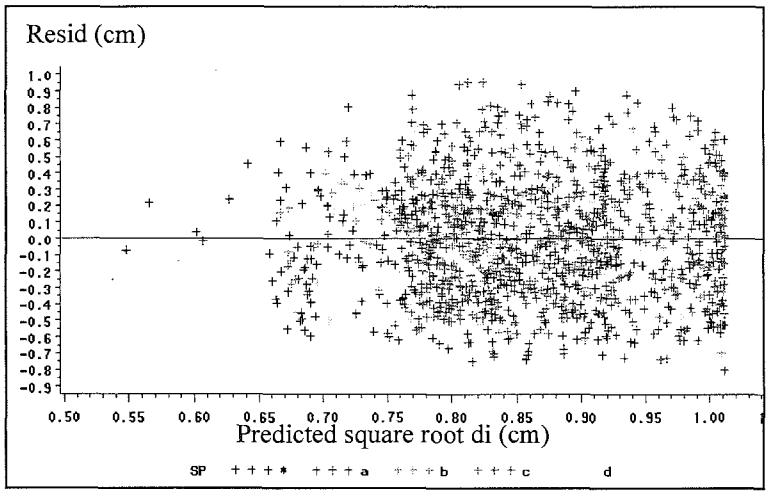
Appendix 4.14a. Residual patterns of selected linear model for four final selected species groups for PT. ITCI data, drawn from Equation [8.b]



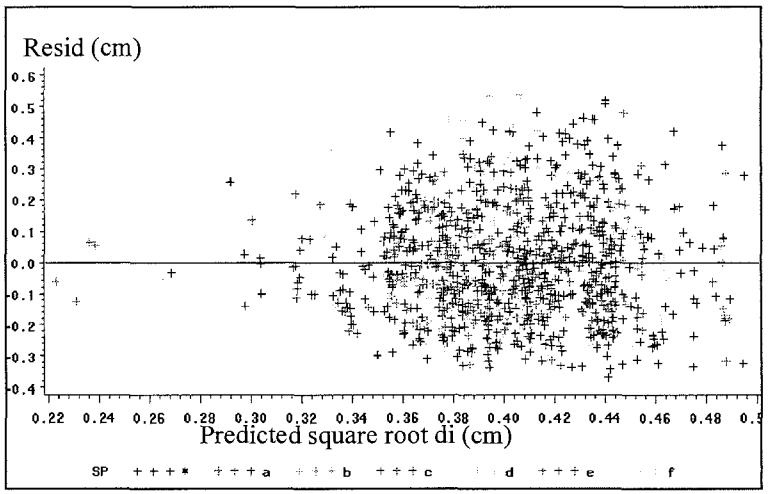
Group LUF



Group LMUS

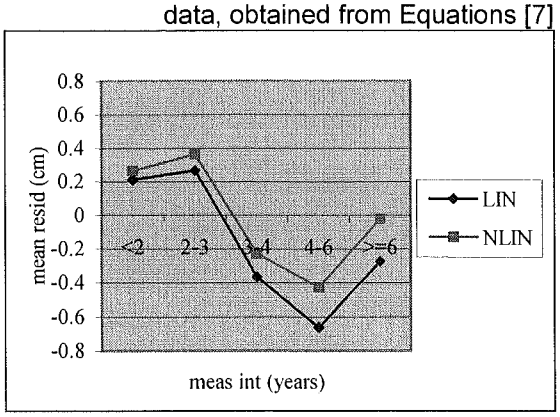


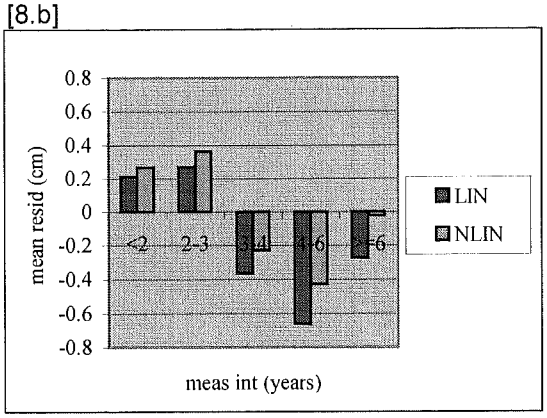
Group MeSF



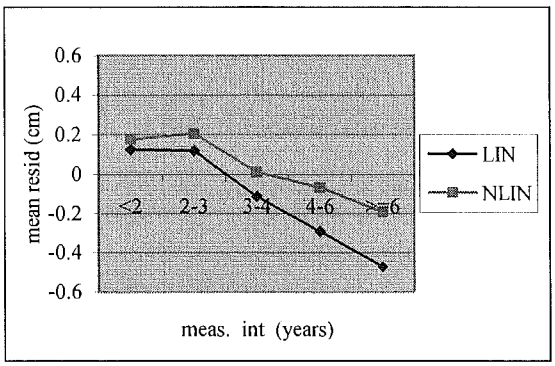
Group SmaS

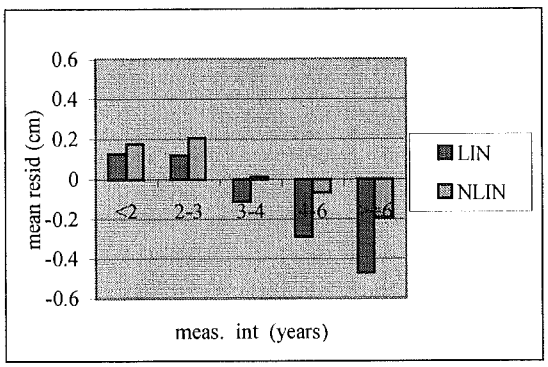
Appendix 4.15. Mean residuals of predicted diameter (d2)over different actual interval lengths between measurements, for four final selected species groups for PT. ITCI data, obtained from Equations [7] and [8.b]



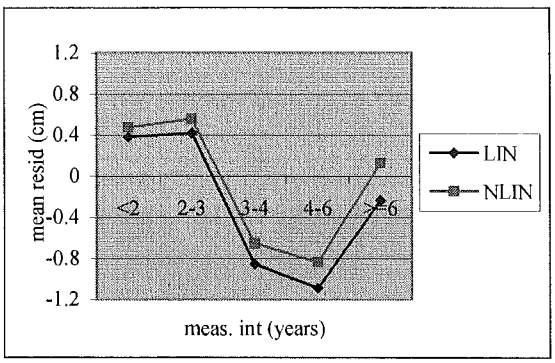


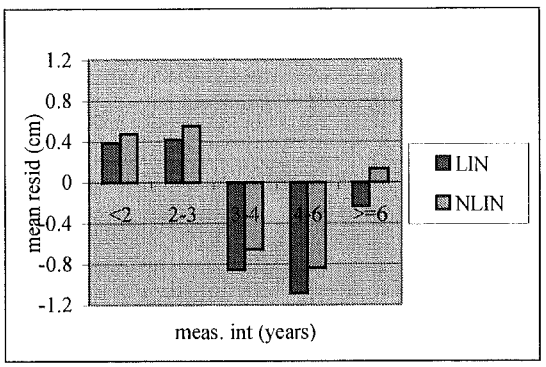
Large and other faster growing species (Group LUF)



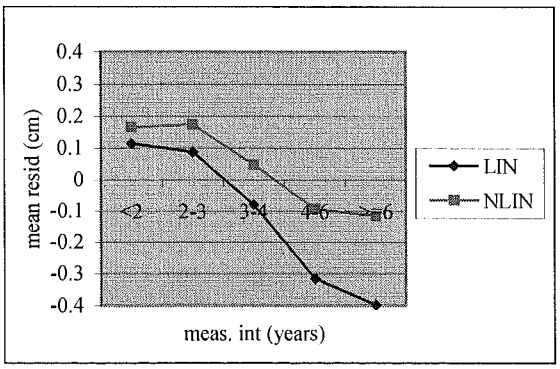


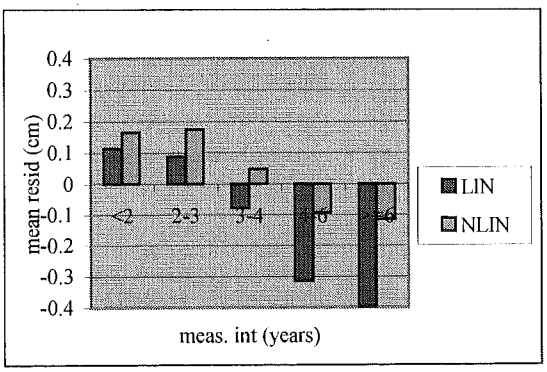
Large, medium, and other slower growing species (Group LMUS)





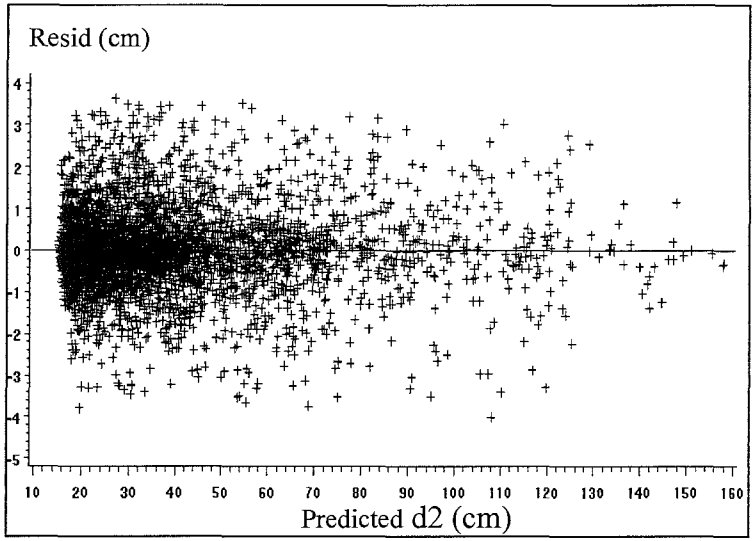
Medium and small faster growing species (Group MeSF)

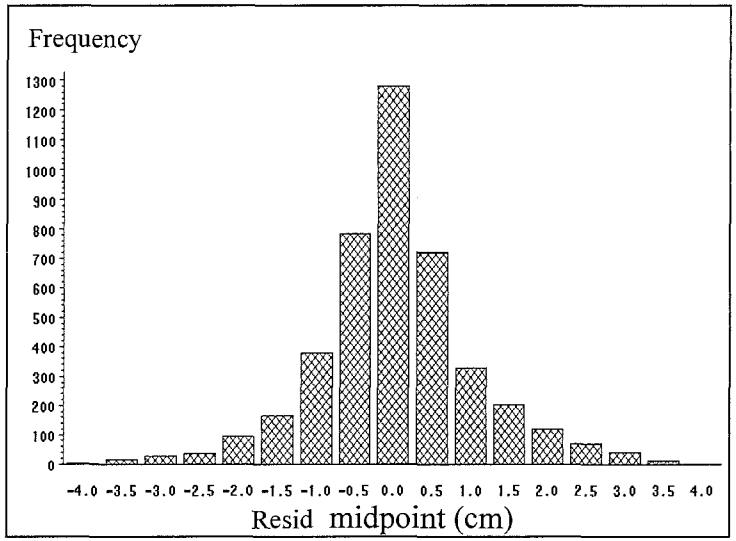




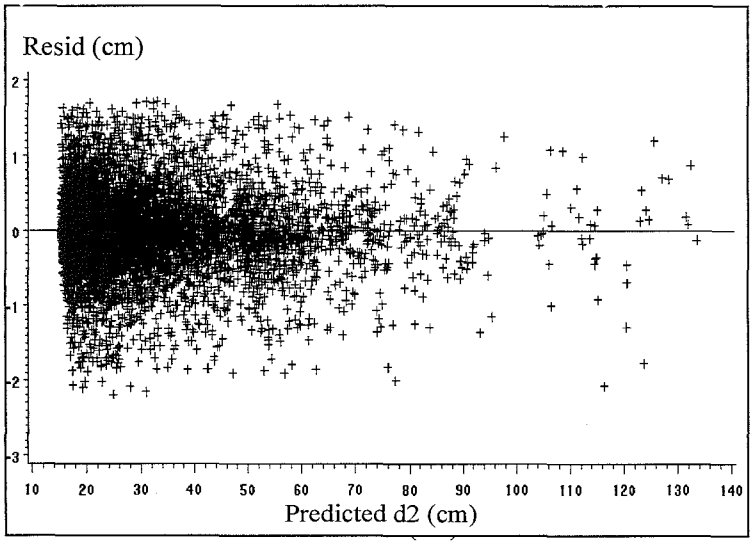
Small slower growing species (Group SmaS)

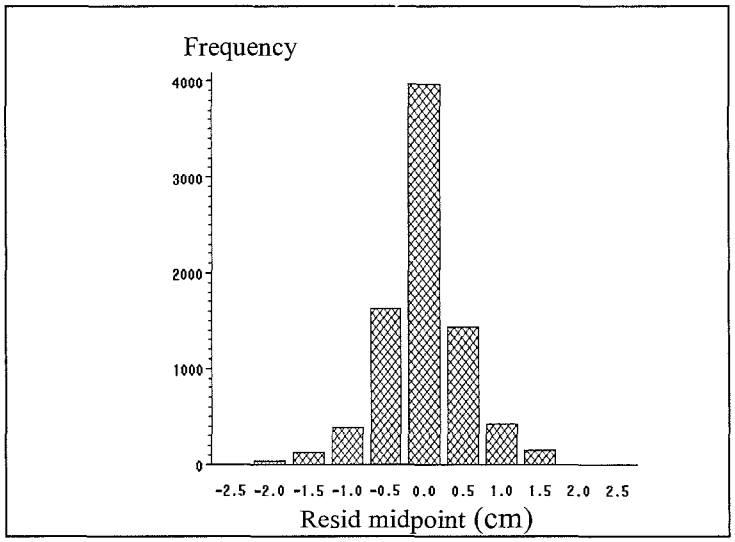
Appendix 4.16a. Residual patterns and distributions of predicted d2 for four final selected species groups for PT. ITCI data, drawn from Equation [8.b].



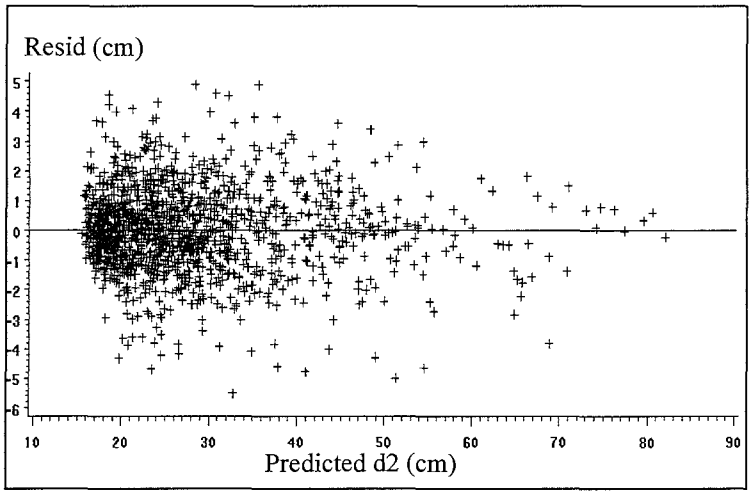


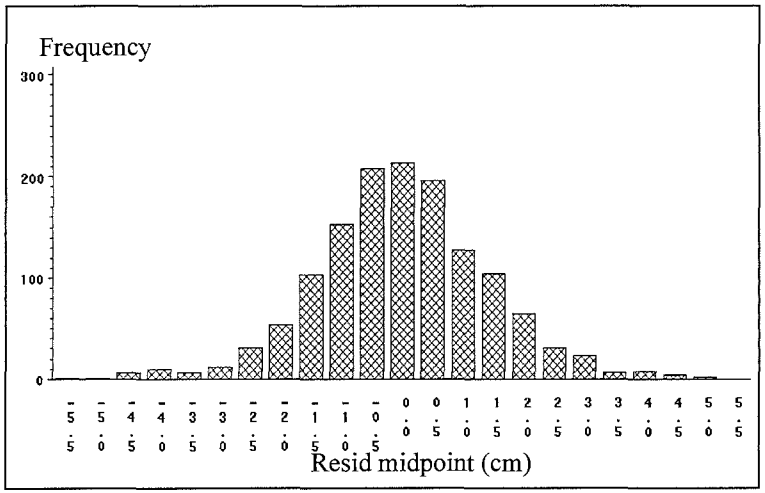
Large and other faster growing species (Group LUF)



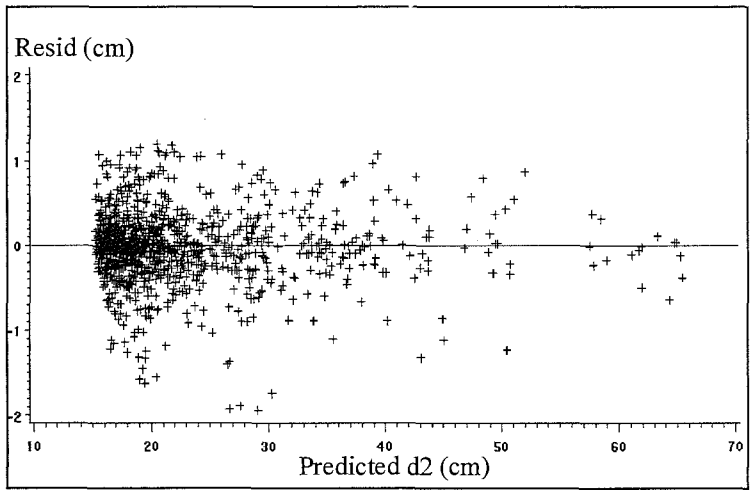


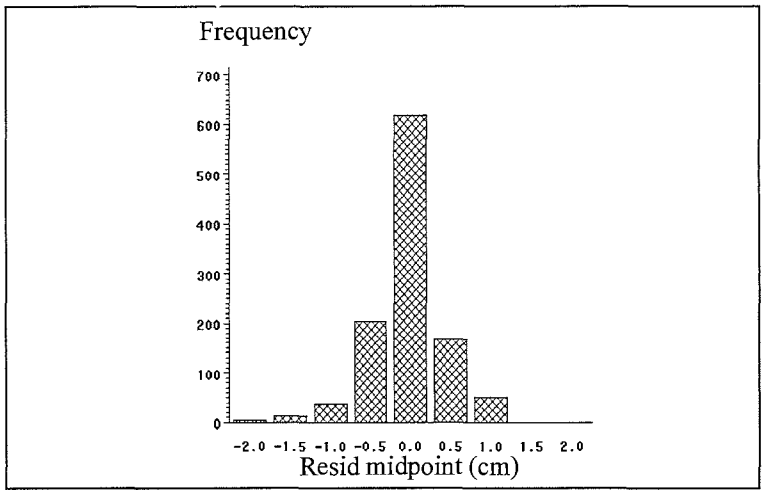
Large, medium, and other slower growing species (Group LMUS)





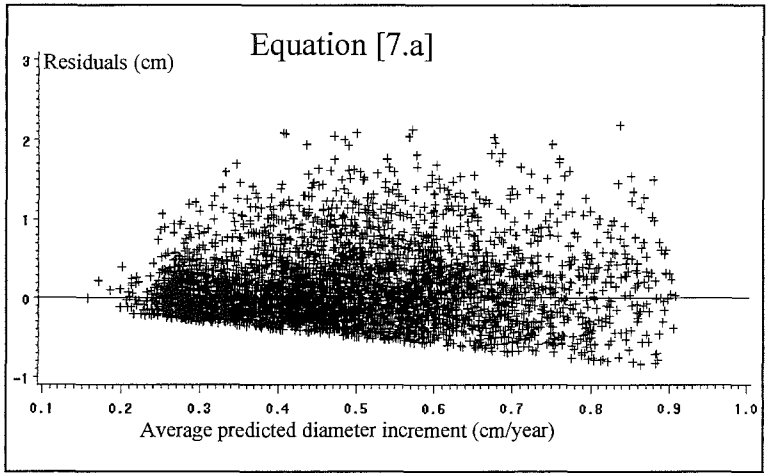
Medium and small faster growing species (Group MeSF)

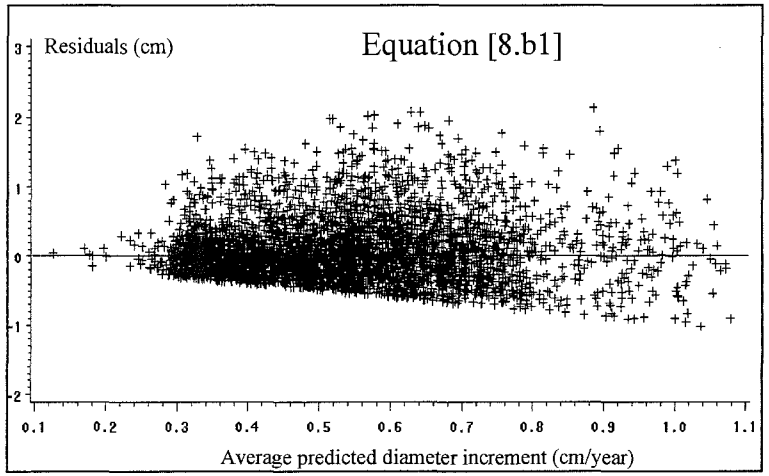




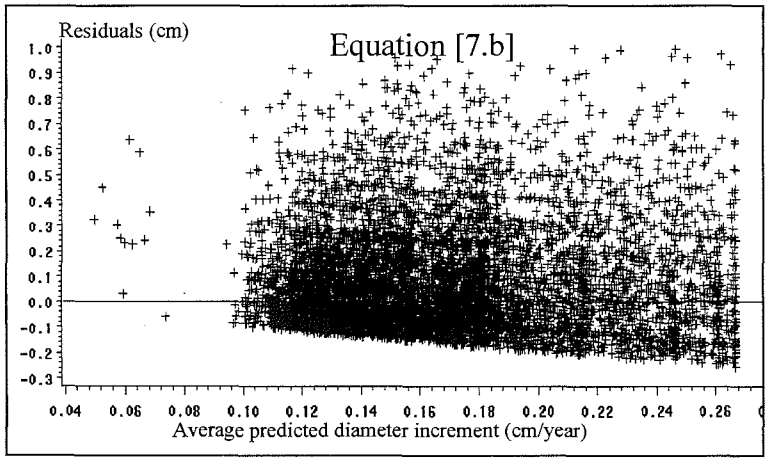
Small slower growing species (Group SmaS)

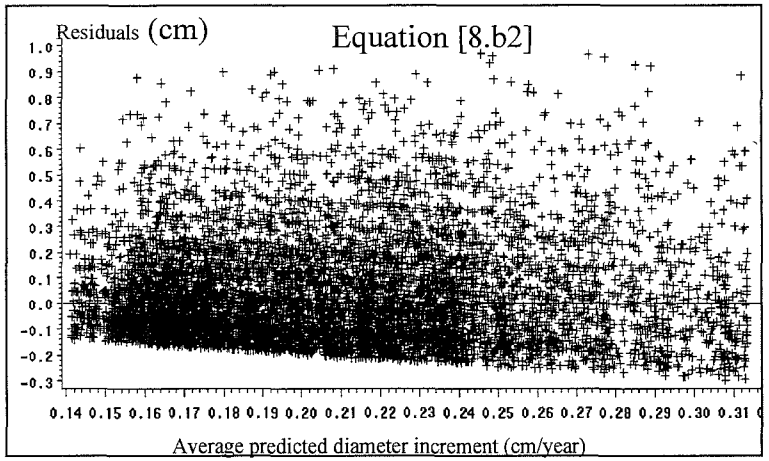
Appendix 4.17. Residual patterns and distributions of predicted diameter increment for four final selected species groups of PT. ITCI data, drawn from non-linear (Equations [7]) and linear (Equation [8.b]) equations



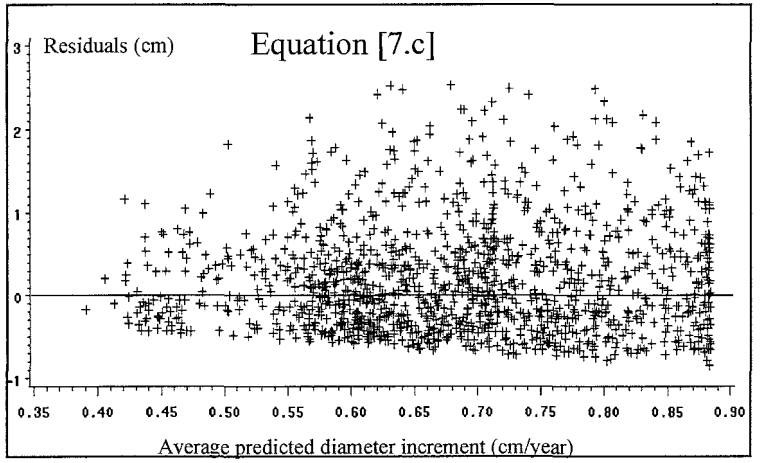


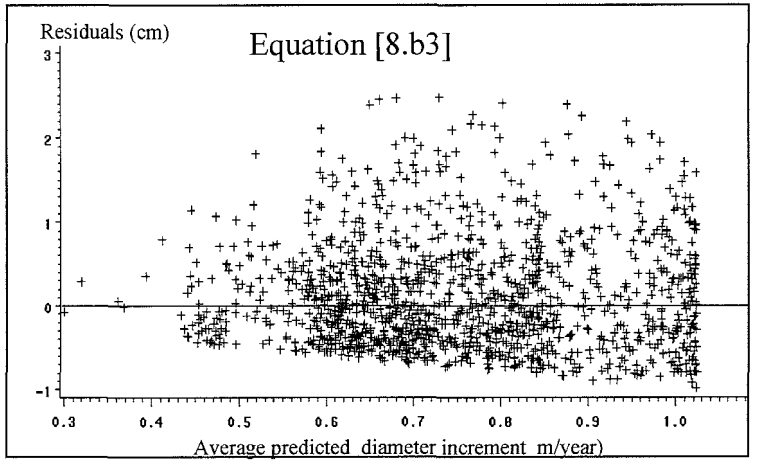
Large and other faster growing species (Group LUF)



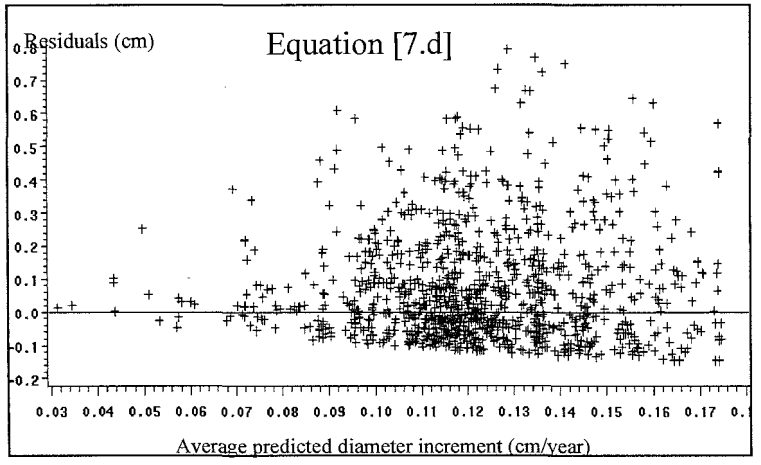


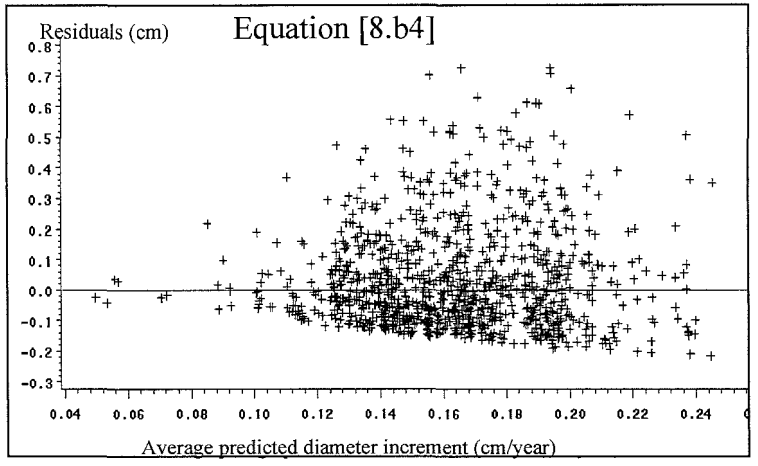
Large, medium, and other slower growing species (Group LMUS)





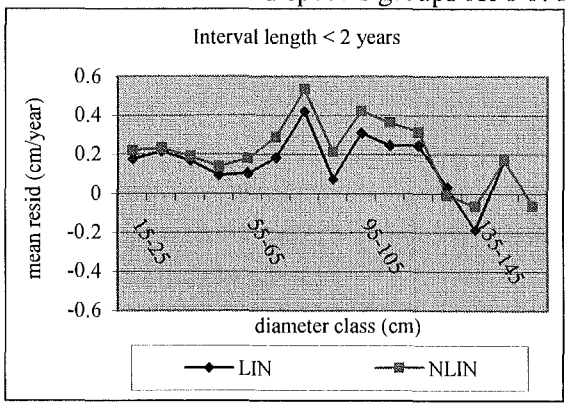
Medium and small faster growing species (Group MeSF)

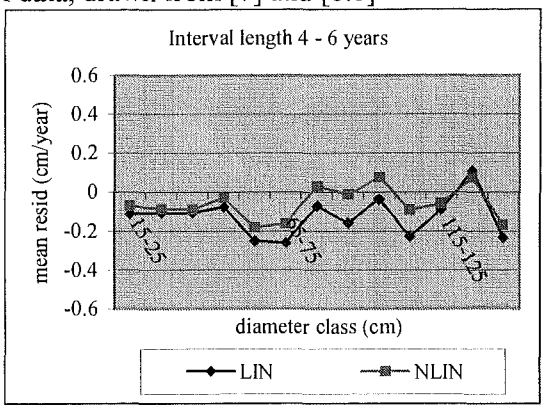




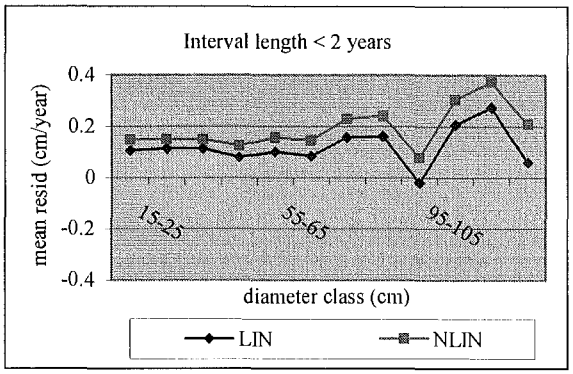
Small slower growing species (Group SmaS)

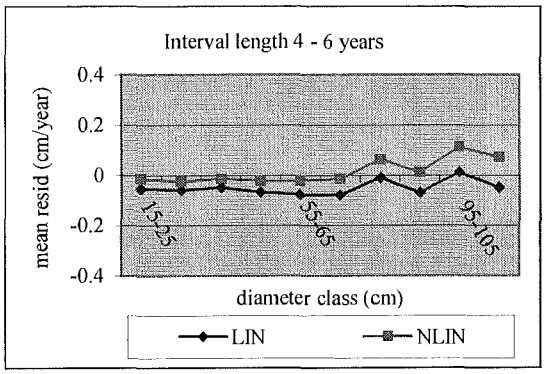
Appendix 4.18. Mean residuals of predicted di over 10 cm diameter class for four final selected species groups for PT. ITCI data, drawn from [7] and [8.b]



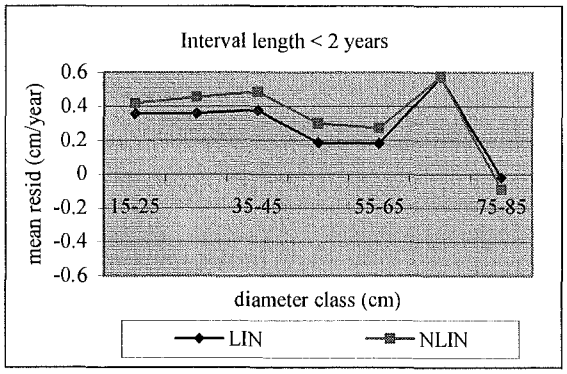


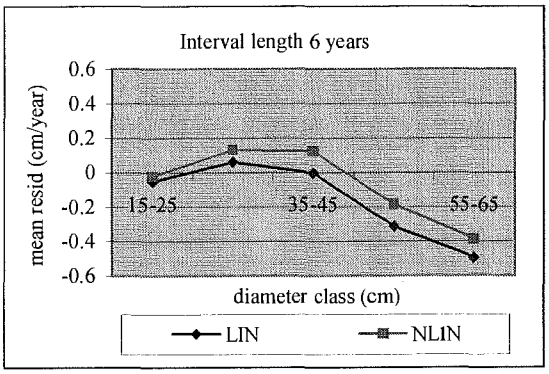
Large and other faster growing species (Group LUF)



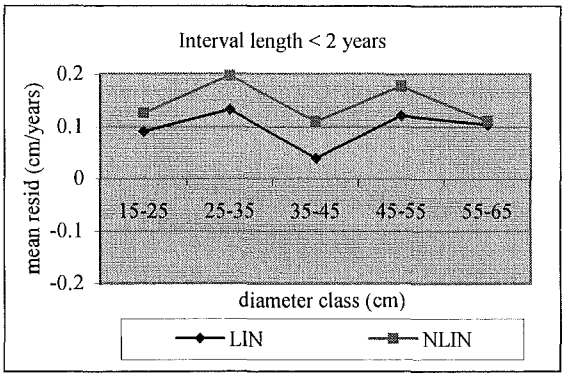


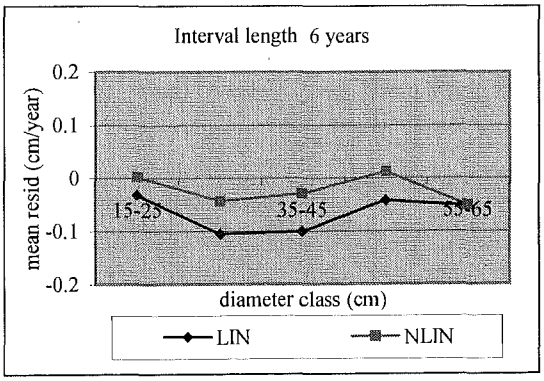
Large, medium, and other slower growing species (Group LMUS)





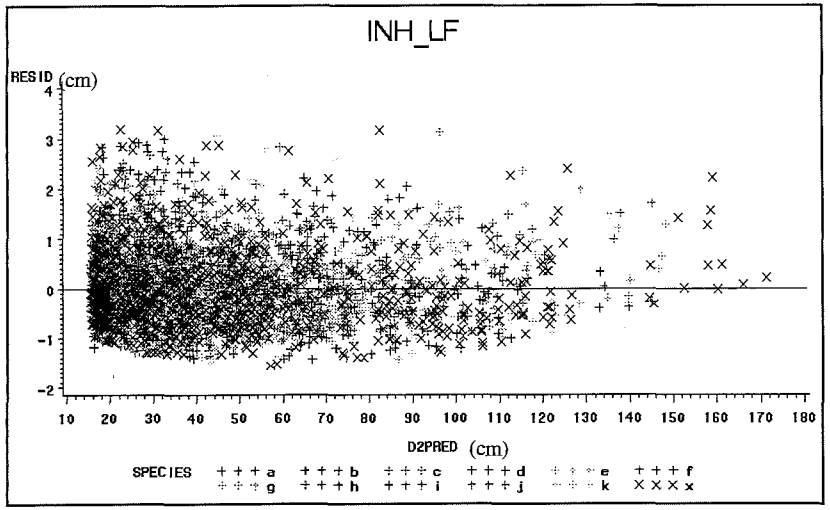
Medium and small faster growing species (Group MeSF)

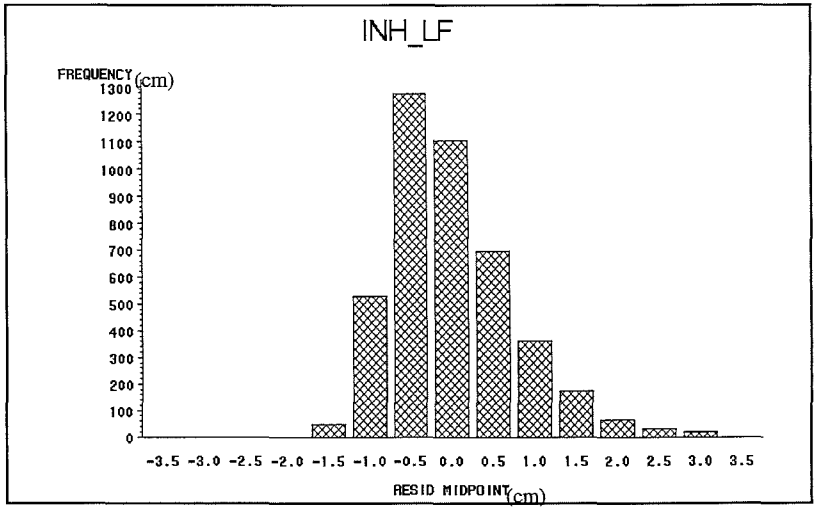




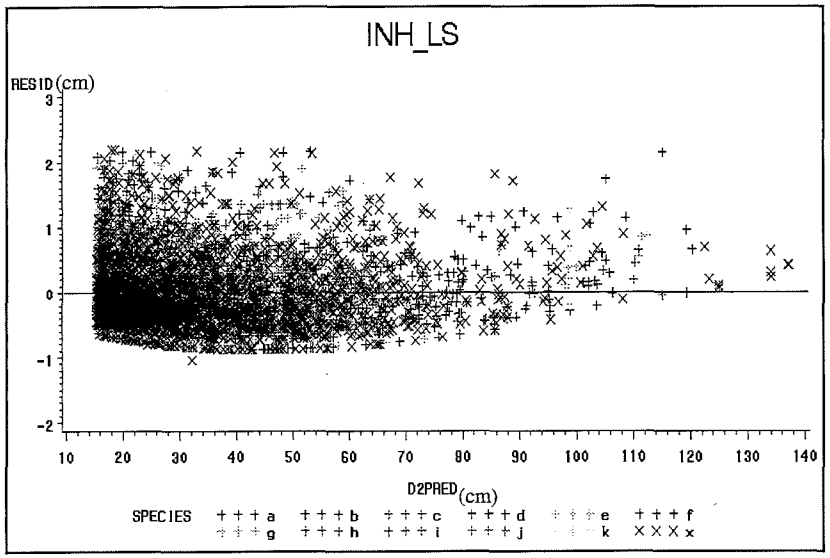
Small slower growing species (Group SmaS)

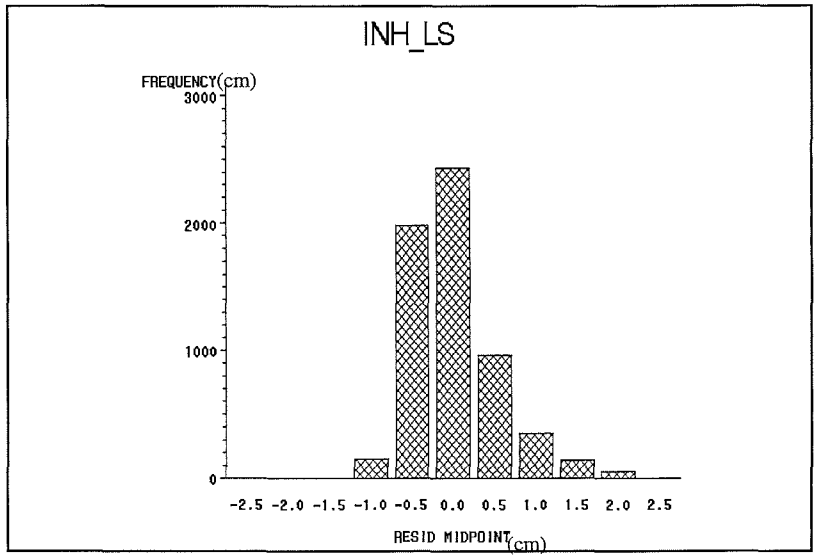
Appendix 4.19b. Residual patterns and distributions for 5 final selected species groups for PT. INHUTANI I data, obtained from Equation [7]



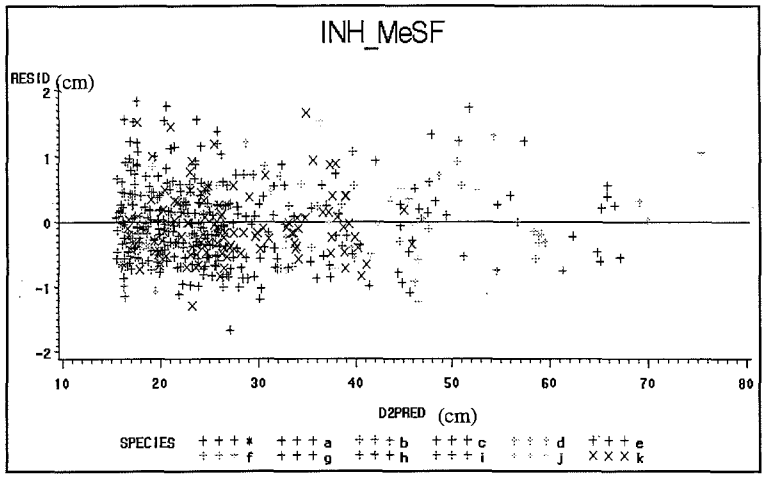


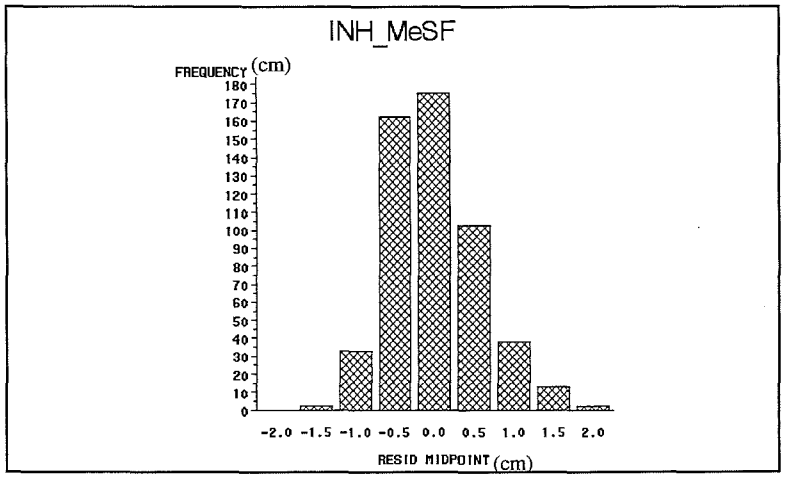
Large faster growing species (Group LF)



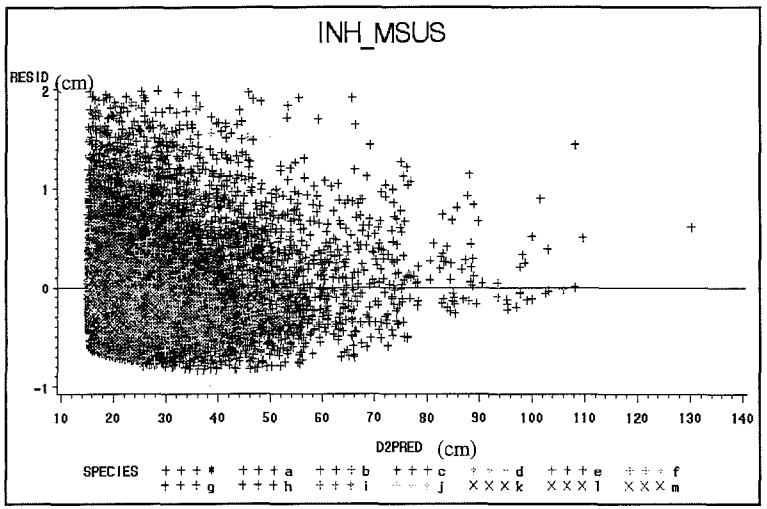


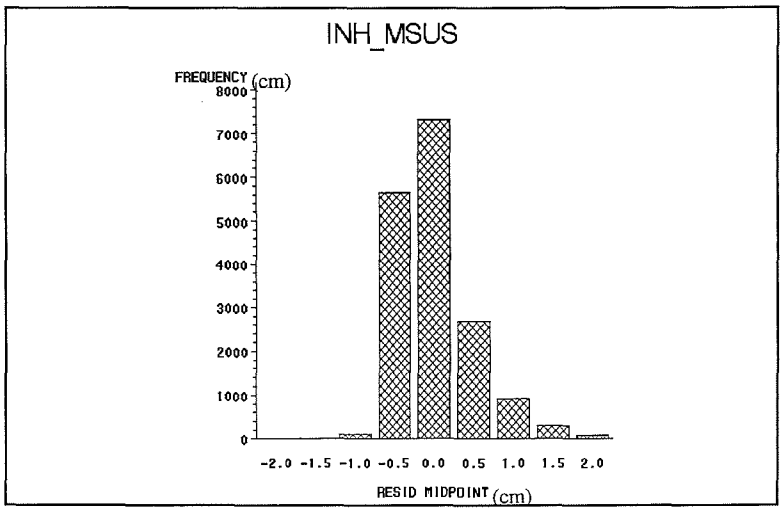
Large slower growing species (Group LS)



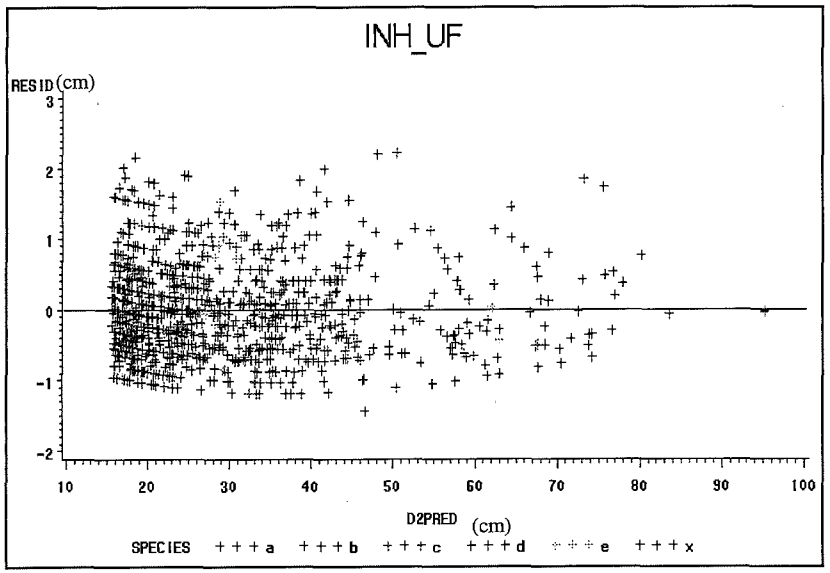


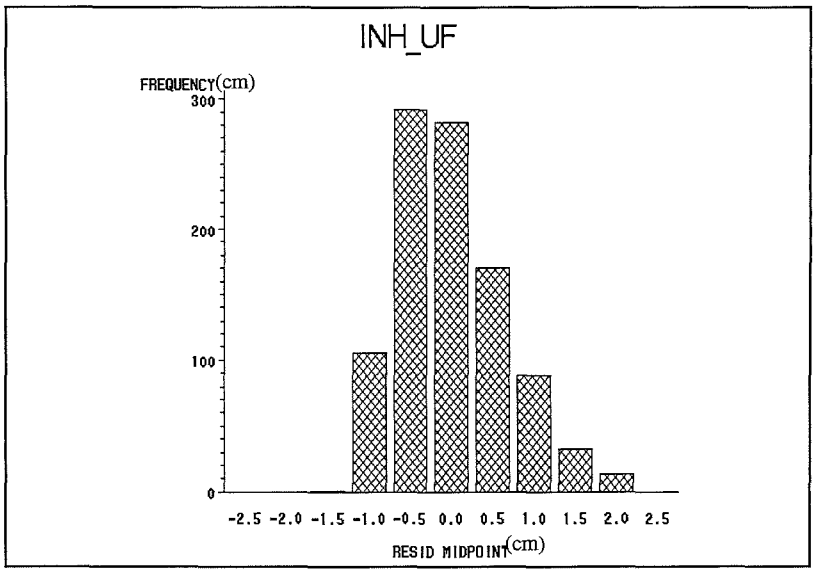
Medium and small faster growing species (Group MeSF)





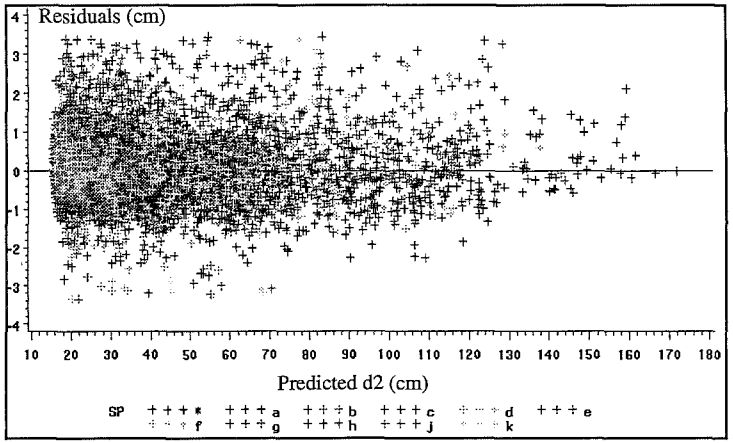
Medium, small, and other slower growing species (Group MSUS)

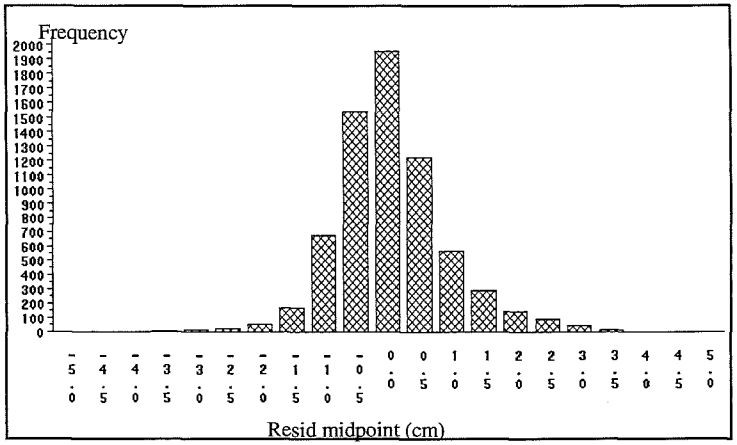




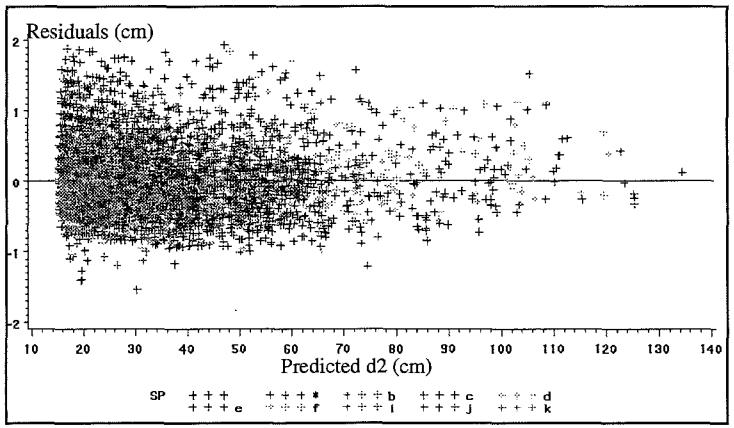
Other faster growing species (Group UF)

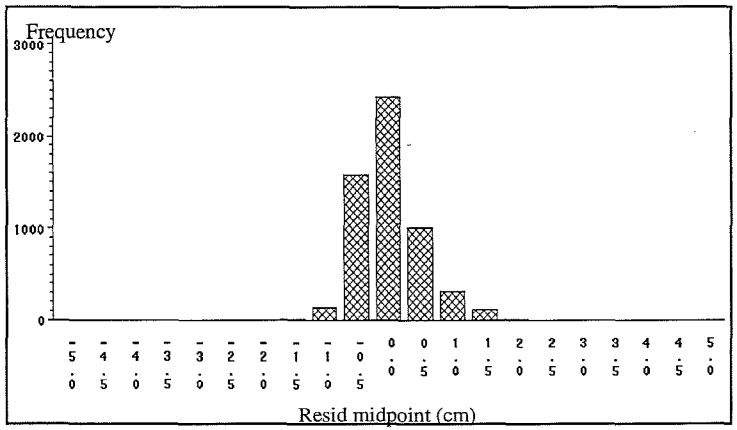
Appendix 4.20a. Residual patterns and distributions for four species groups for the combined data, drawn from Equation [7]



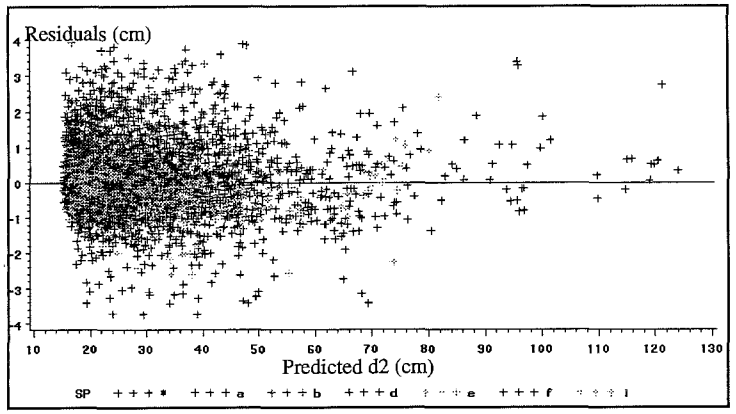


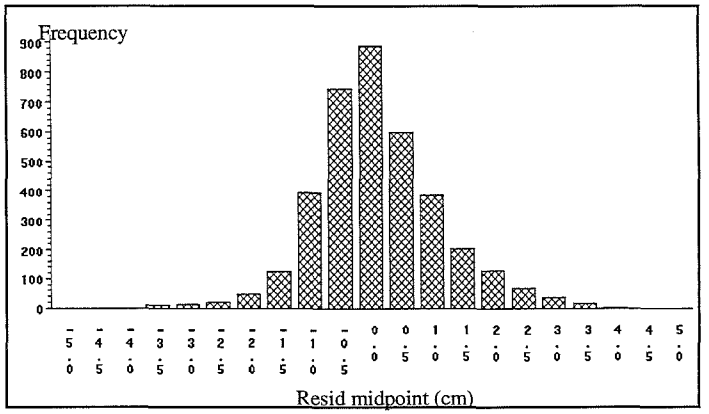
Faster growing dipterocarp species (Group DF)



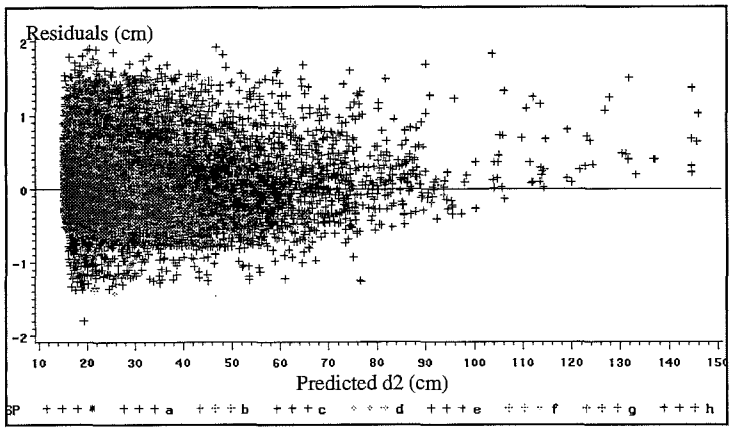


Slower growing dipterocarp species (Group DS)



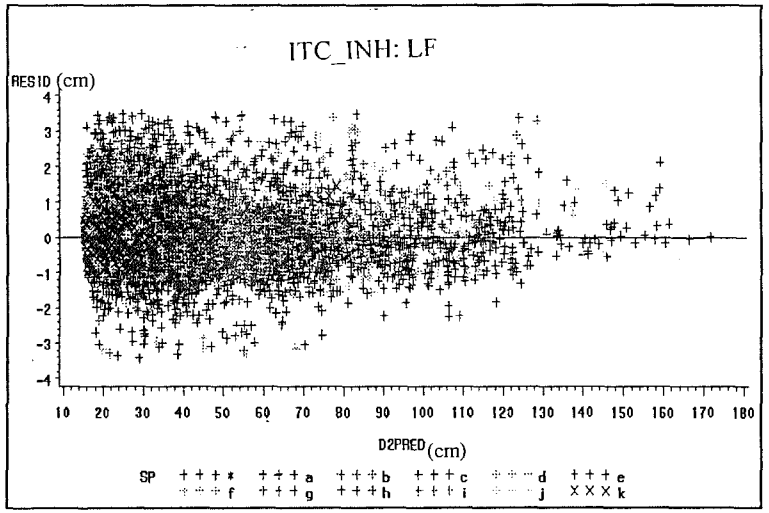


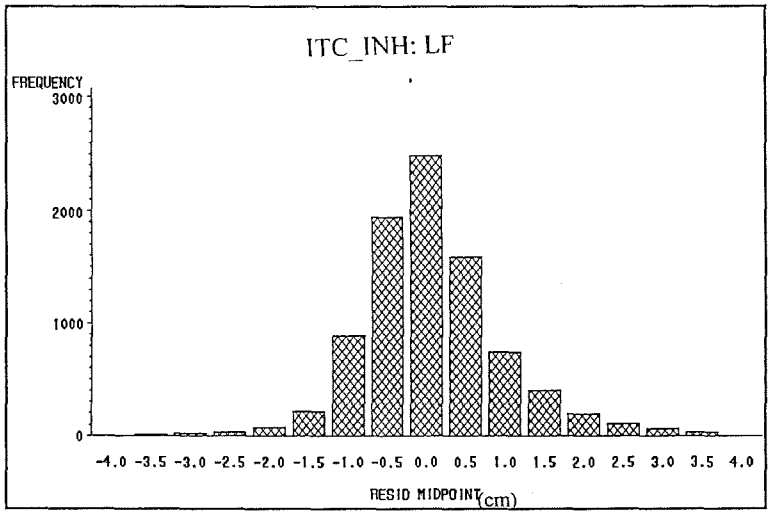
Faster growing non-dipterocarp species (Group NF)



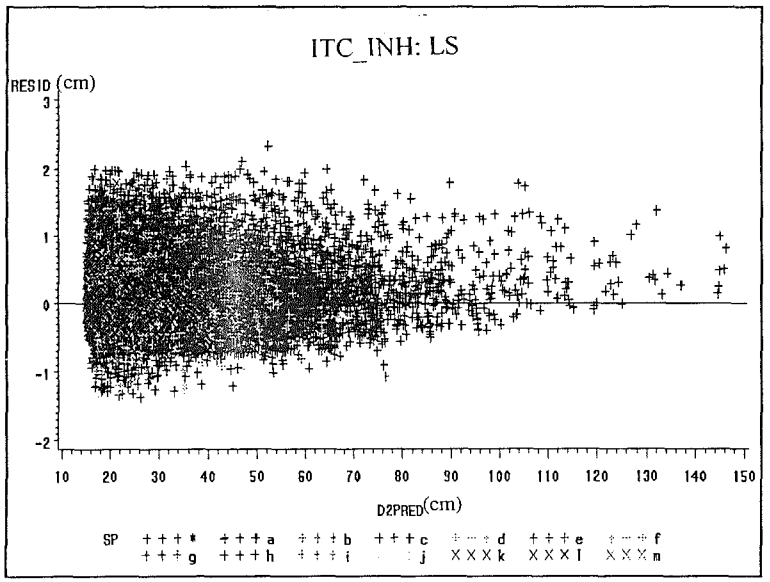
Slower growing non-dipterocarp species (Group NS)

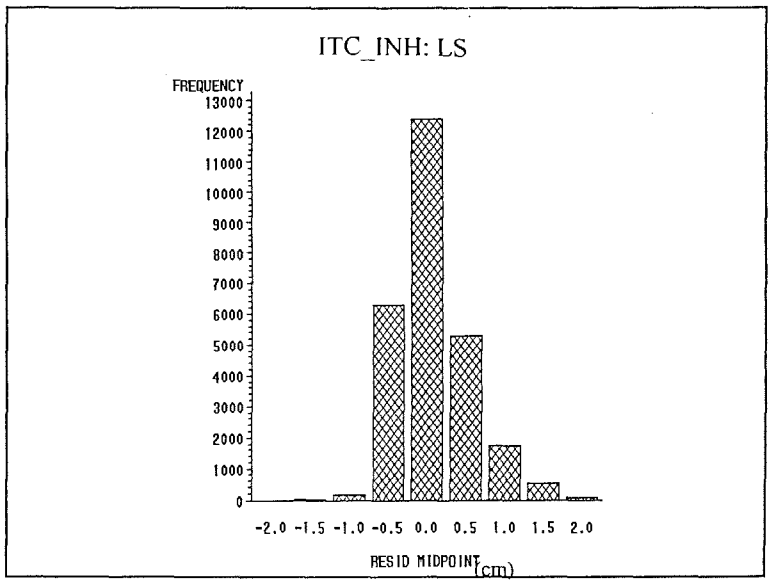
Appendix 4.21a. Residual patterns and distributions for 8 species groups for the combined data, drawn from Equation [7]



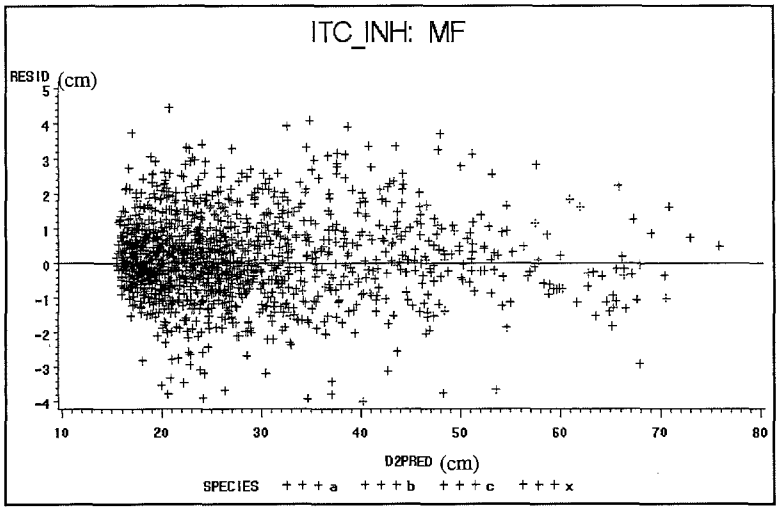


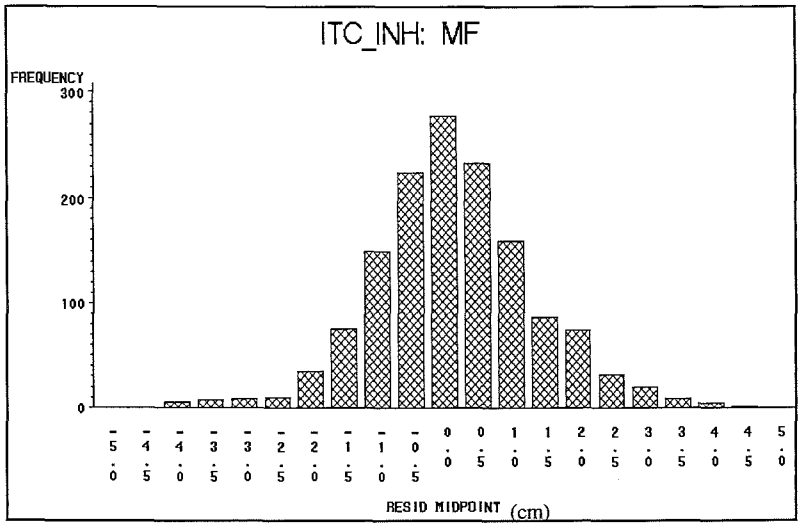
Large faster growing species (Group LF)



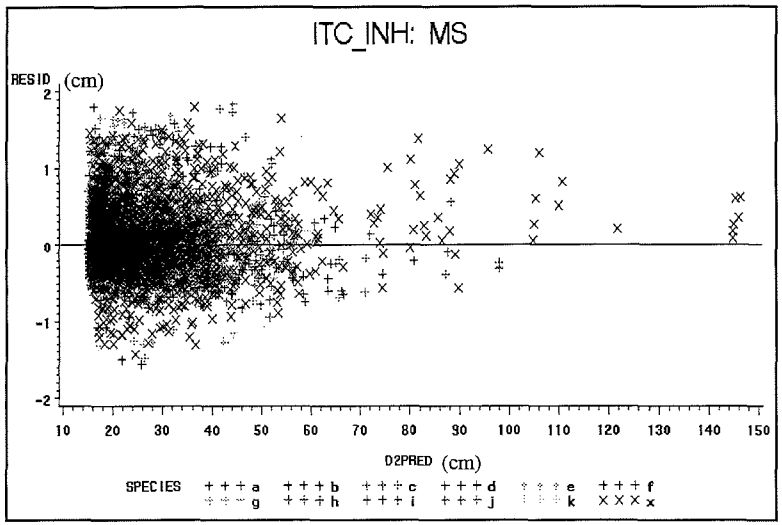


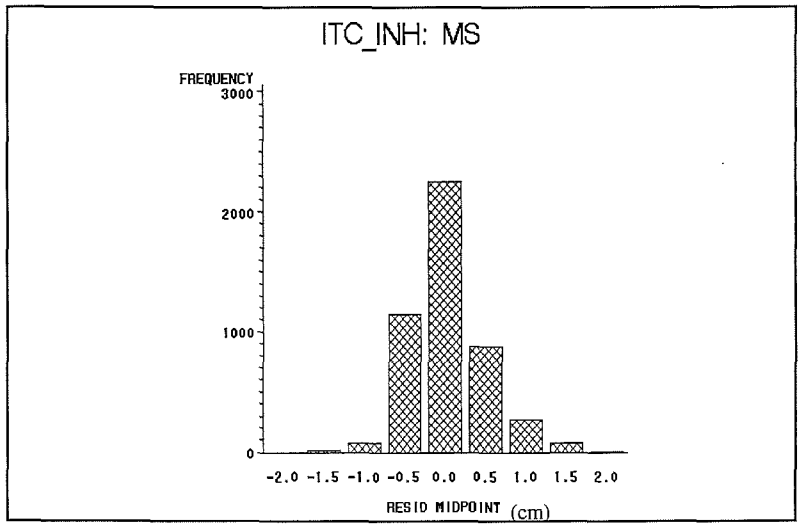
Large slower growing species (Group LS)



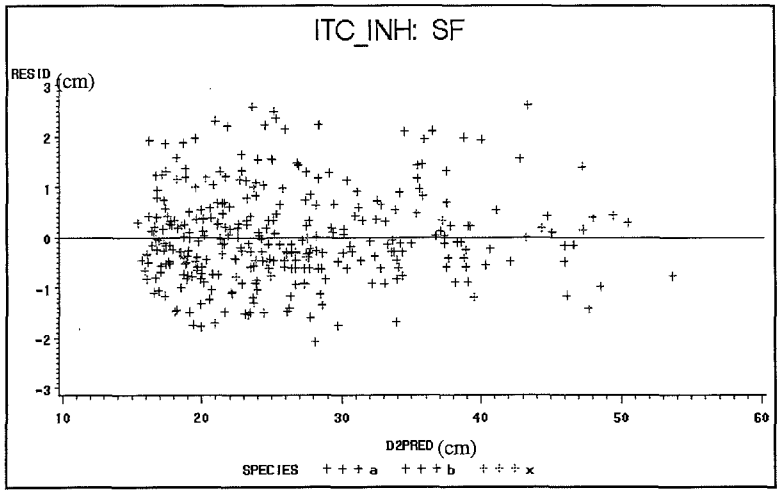


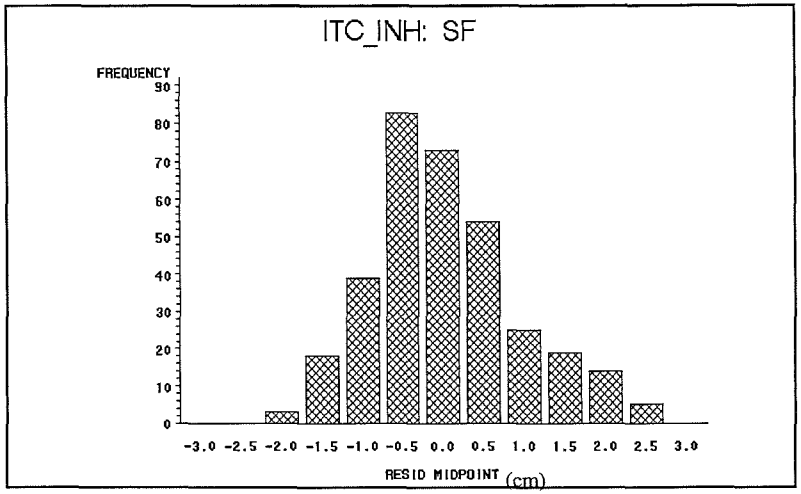
Medium faster growing species (Group MF)



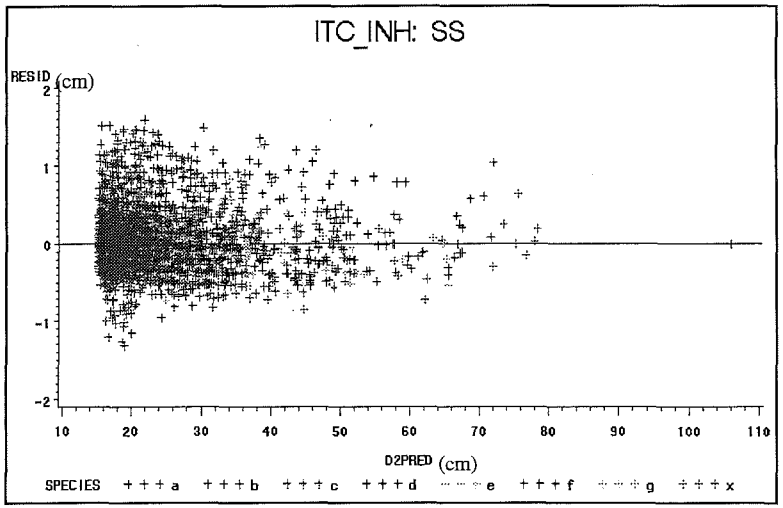


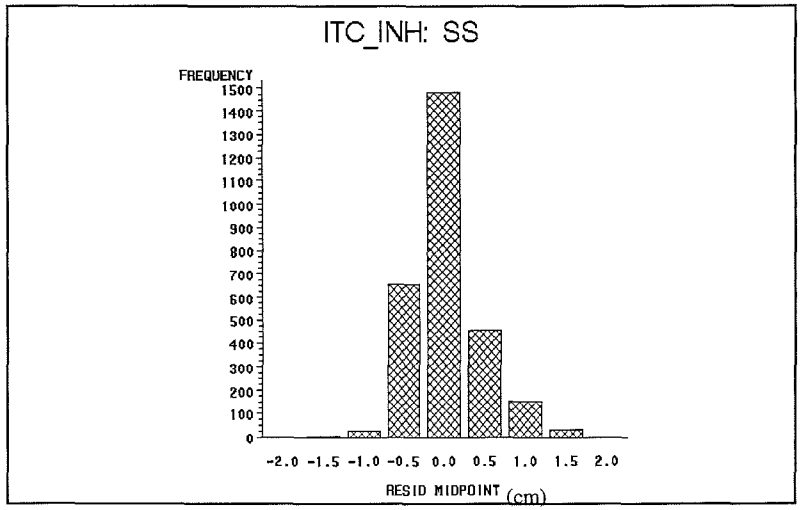
Medium slower growing species (Group MS)



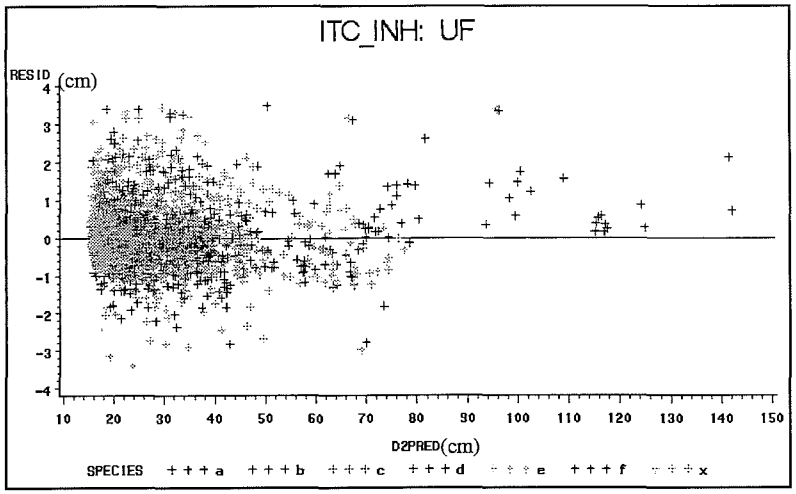


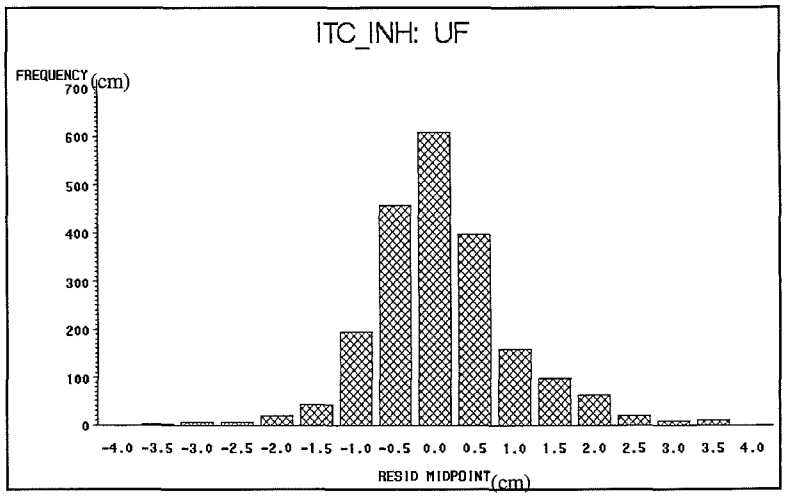
Small faster growing species (Group SF)



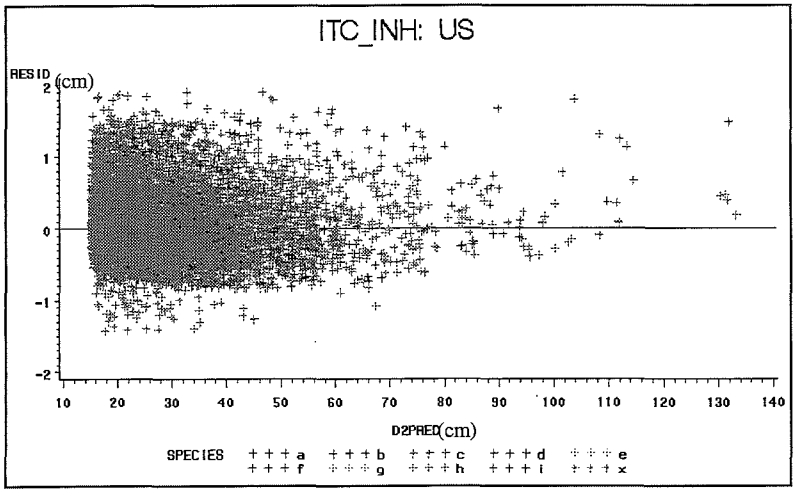


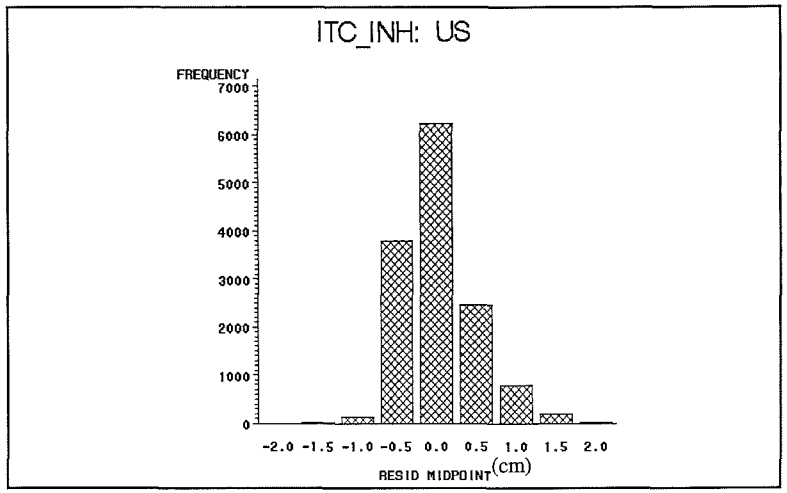
Small slower growing species (Group SS)





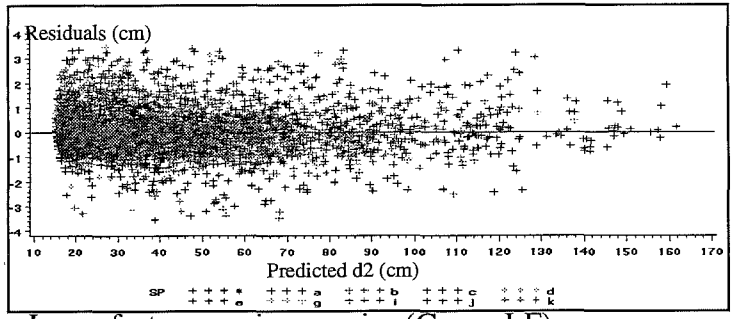
Other faster growing species (Group UF)

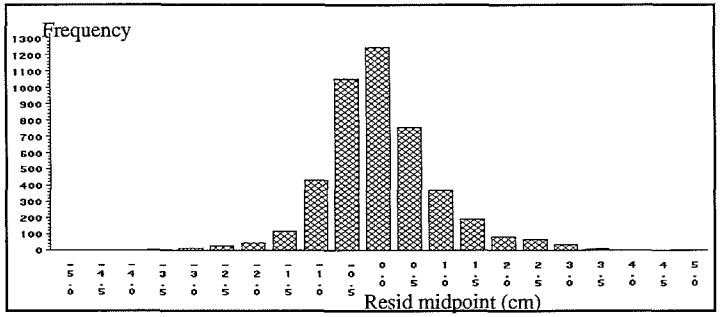




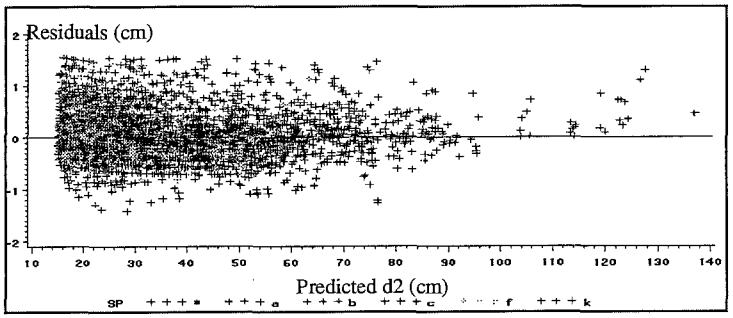
Other slower growing species (Group US)

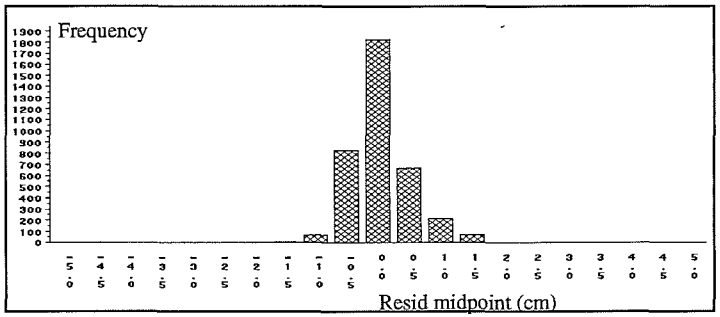
Appendix 4.22a. Residual patterns and distributions for 10 species groups for the combined data, drawn from Equation [7]



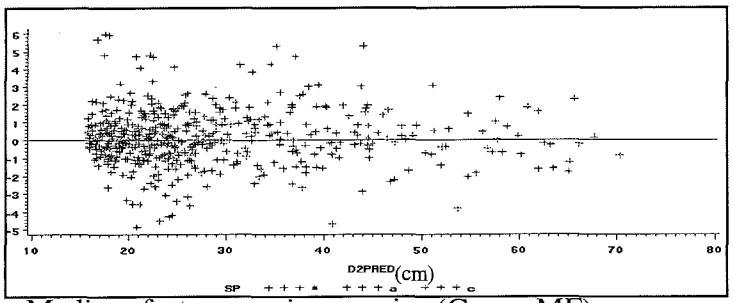


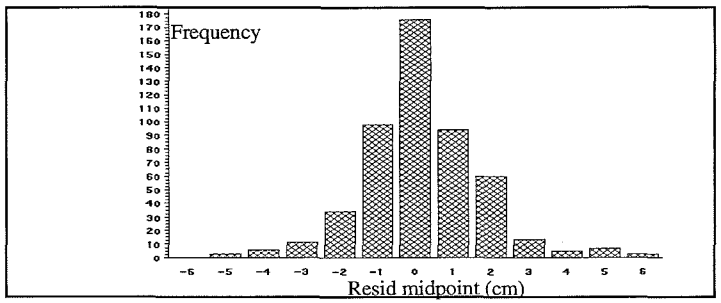
Large faster growing species (Group LF)



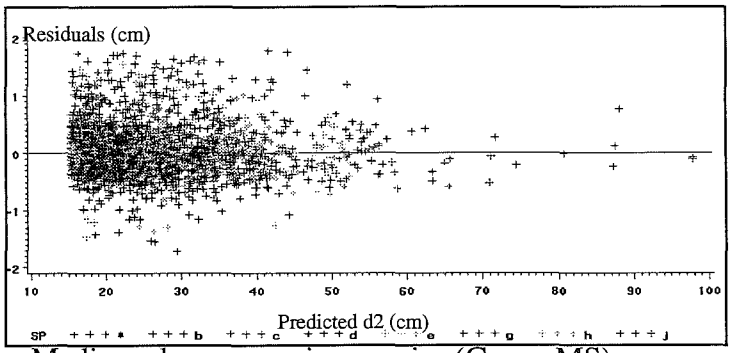


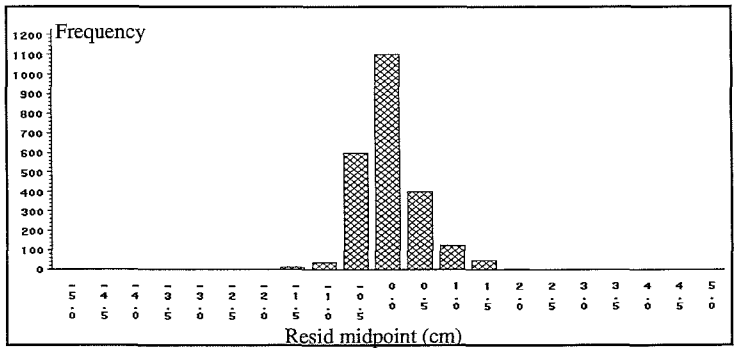
Large slower growing species (Group LS)



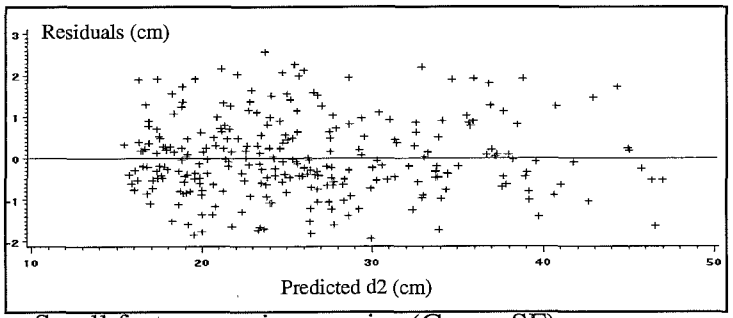


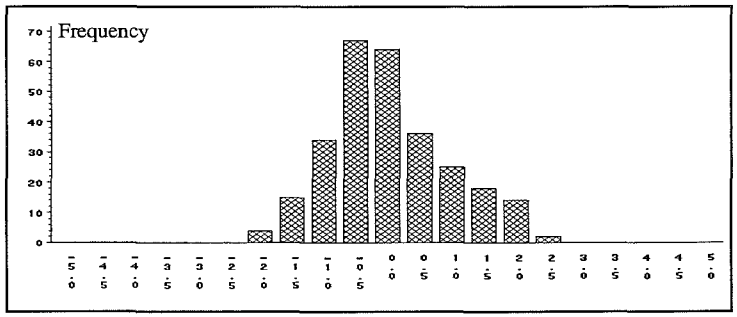
Medium faster growing species (Group MF)



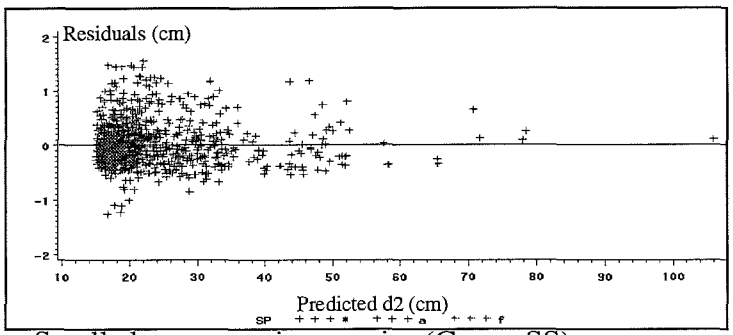


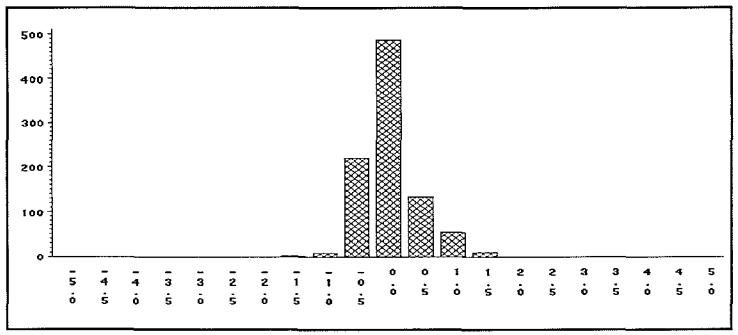
Medium slower growing species (Group MS)



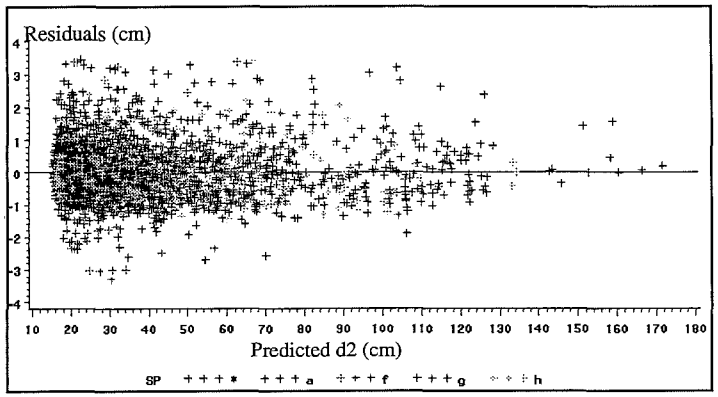


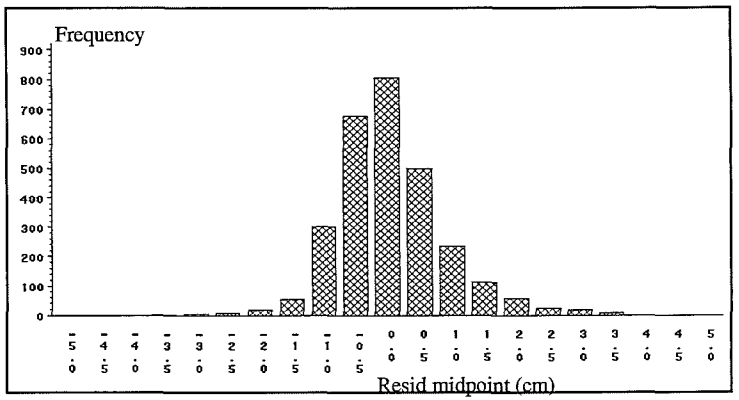
Small faster growing species (Group SF)



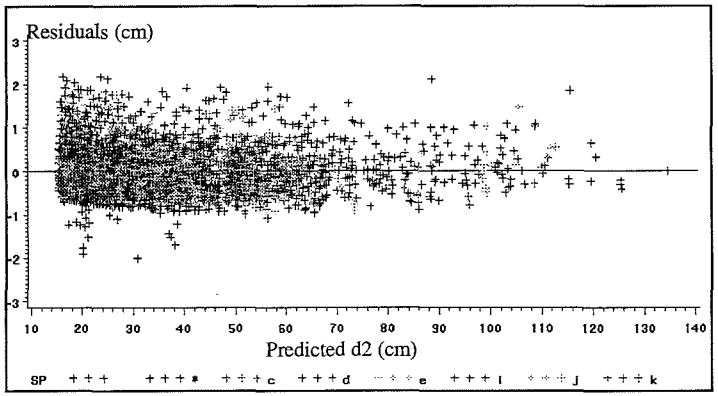


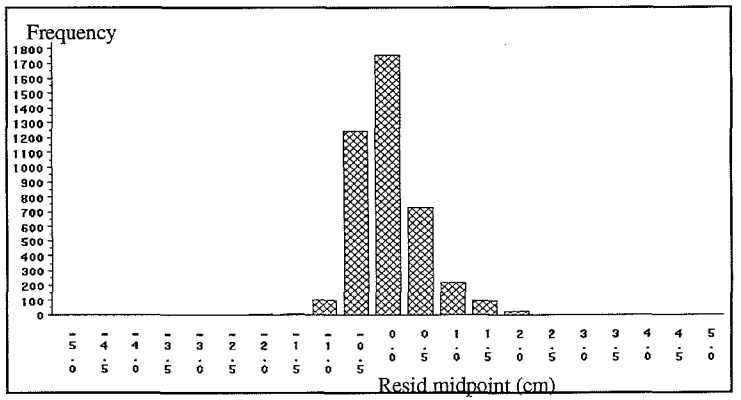
Small slower growing species (Group SS)



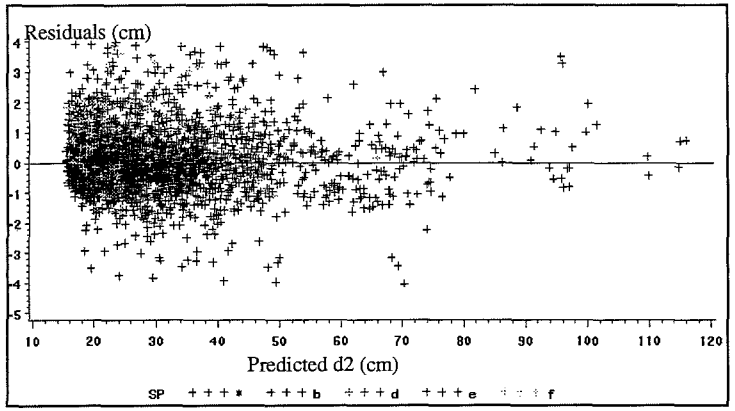


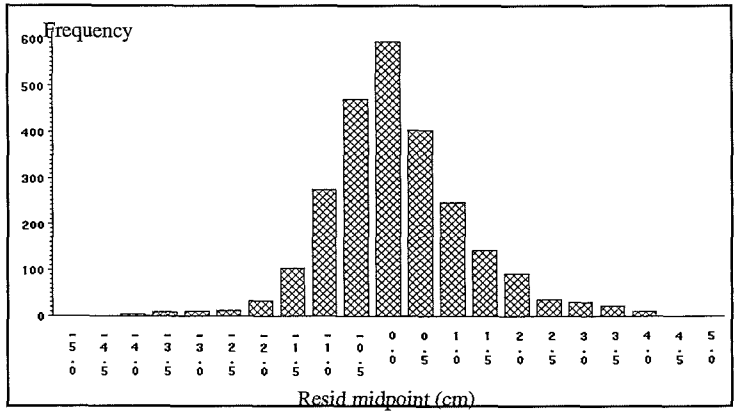
Faster growing dipterocarp species (Group DF)



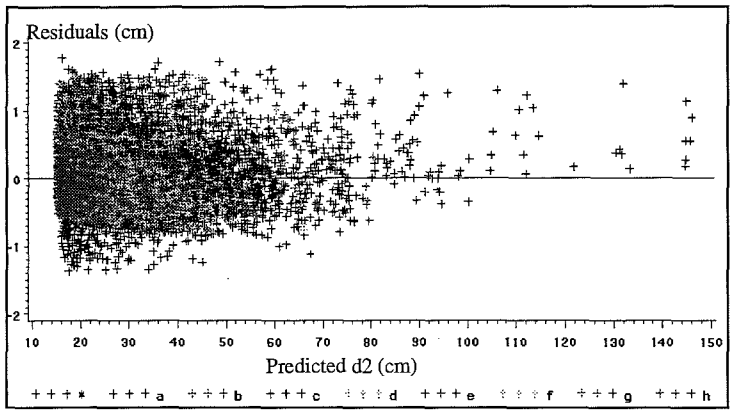


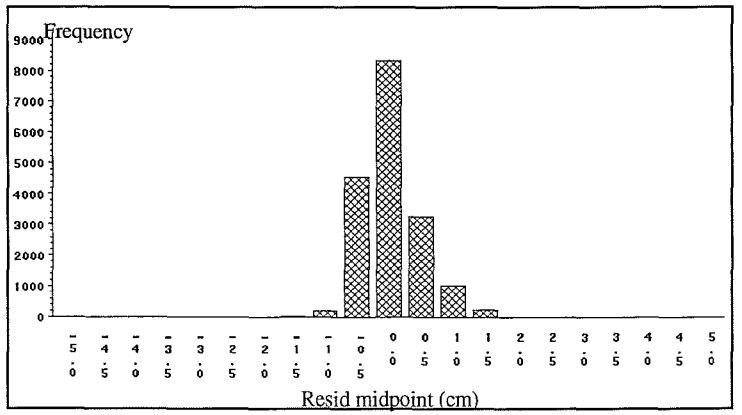
Slower growing dipterocarp species (Group DS)





Faster growing non-dipterocarp species (Group NF)





Slower growing non-dipterocarp species (Group NS)

Appendix 4.23. Procedures used to transform Pambudhi's (1997) model to difference equation and for model comparison

A. Pambudhi's (1997) model

Group Shorea

$Lbai = -0.879 + 0.854*lba - 0.00029*d^2 - 0.0013*N - 0.199*yr$

Group Dipterocarp (other than Shorea)

$Lbai = -1.149 + 0.712*lba - 0.0271*yr$

Group Commercials (non-dipterocarps)

$Lbai = -0.800 + 0.729*lba - 0.0226*SBA$

Group Miscellaneous

$Lbai = -3.669 + 1.057*lba - 2.73.10^{-7}*ba^2 + 1.231*hd - 0.0017*N - 0.326*yr$

Where :

Lbai	:	log tree basal area increment
ba	:	tree basal area
SBA	:	stand basal area
N	:	number of trees per ha
yr	:	time since logging, takes up the value 1 and –1 for 1 and 5 years after logging respectively
d	:	tree diameter
lba	:	log basal area
hd	:	height diameter ratio (hd=hcp/d where hcp = -10.13 + 7.52 ln d)
hcp	:	height at crown point.

Each of these models was fitted to PT. INHUTANI I data (logged plots), then transform into different equations as follows, and residual plots of future diameter ($d_{2act} - d_{2predt}$) against predicted values was produced in SAS.

Parameter values of each model was firstly used to obtained $lbai_{pred}$.

$bai_{pred} = Exp\ (lbai_{pred})$

$ba_{2pred} = ba_1 + (bai_{pred}*(t_2-t_1))$

$d_{2pred} = \sqrt{}(ba_{2pred}/(0.25*\pi))$

residuals $= d_{2act} - d_{2pred,}$

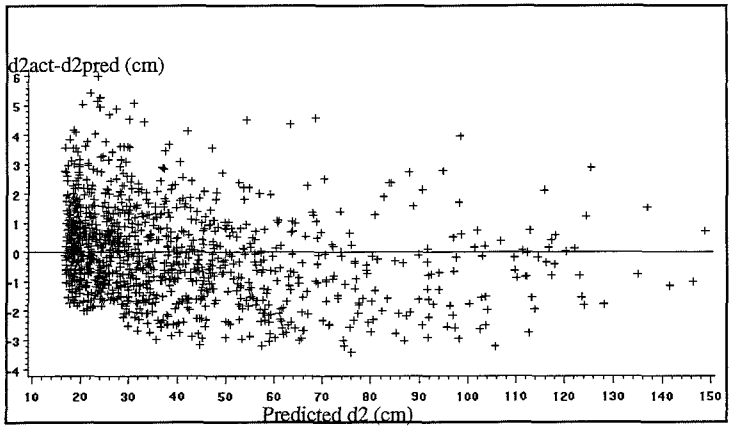
the residual values for each model (each species group) was then plotted against predicted values, resulted in residual plots in Figures 4.25 of Chapter 4.

B. Equation [7.a] to [7.d] (selected models for PT. ITCI data

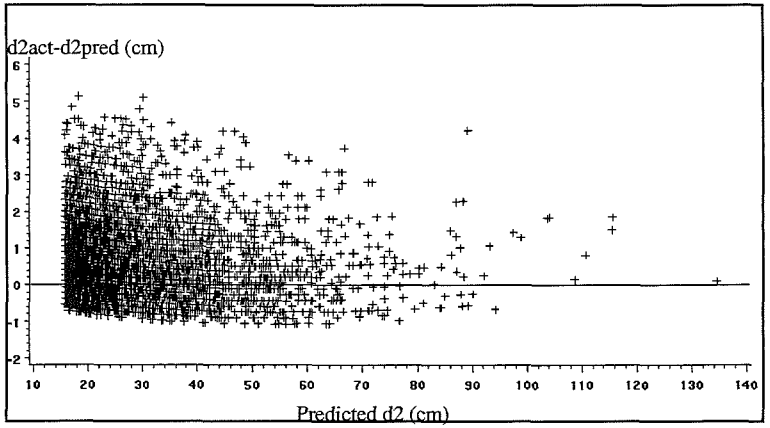
Equations [7.a] to [7.d] were fitted to the same data and residuals ($d_{2act} - d_{2pred}$) were plotted against predicted values, resulted in residual plots in Figures 4.24 of Chapter 4.

C. Comparison of growth trends (predicted growth using the two types of model) with actual growth for some individual species (Figures 4.26) of Chapter 4.

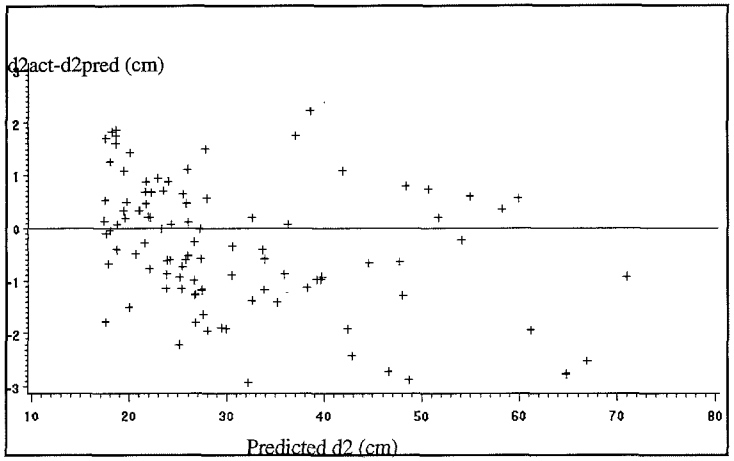
Appendix 4.24a-d. Residual patterns obtained from fitting selected model for four species groups of PT. ITCI to logged-over plots data of PT. INHUTANI I



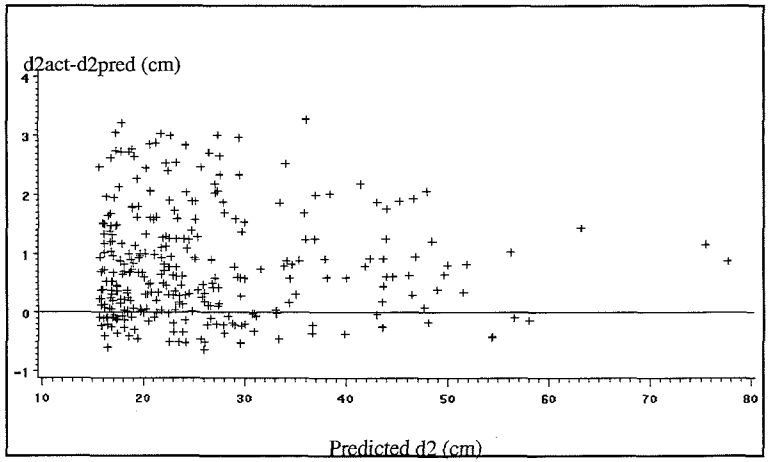
Appendix 4.24a. Group LUF



Appendix 4.24b. Group LMUS

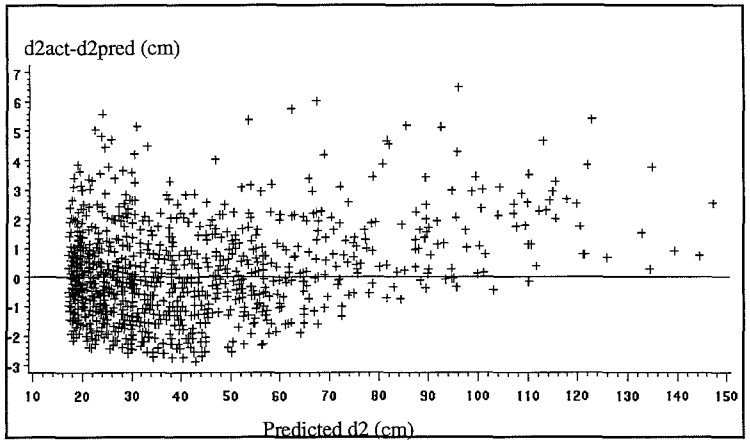


Appendix 4.24c. Group MeSF

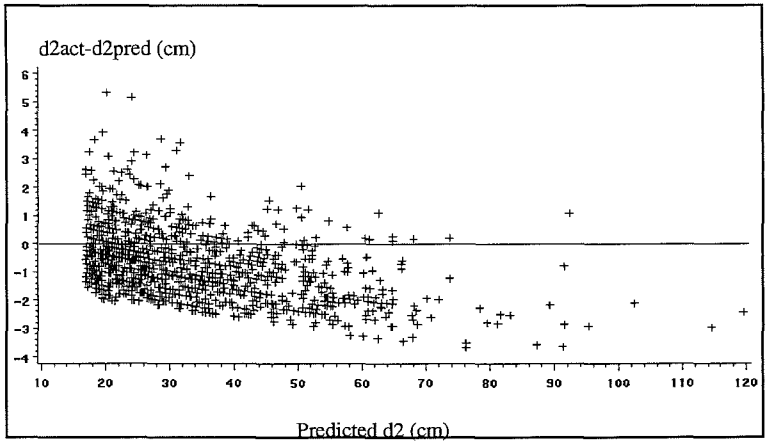


Appendix 4.24d. Group SmaS

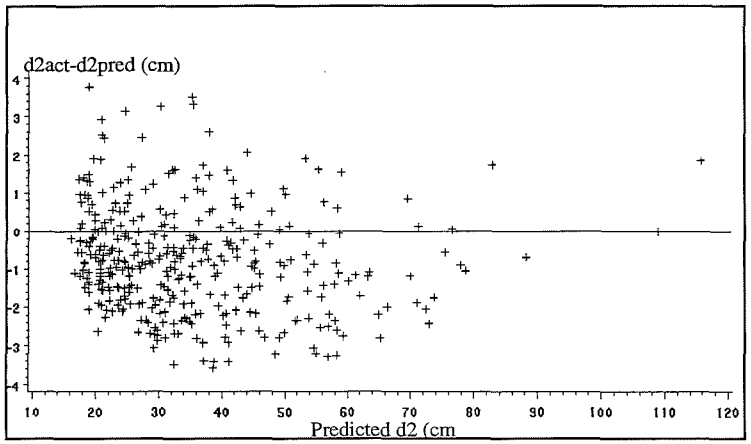
Appendix 4.25a-d. Residual patterns obtained from fitting Pambudi (1997)model to logged plots data of PT. INHUTANI I



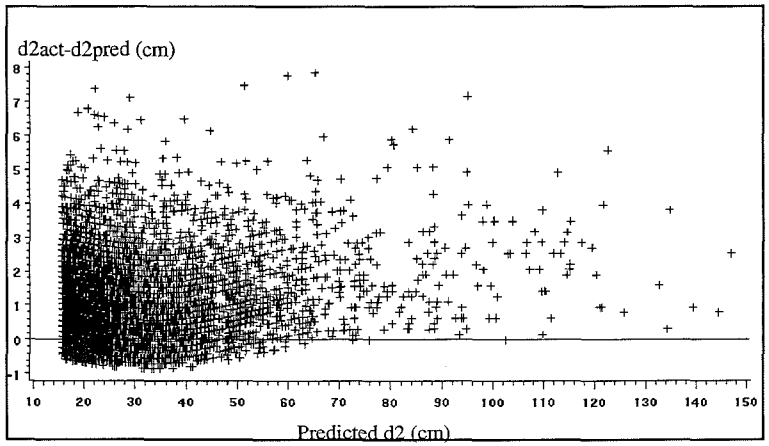
Appendix 4.25a. Group Shorea



Appendix 4.25b. Group Other dipterocarps

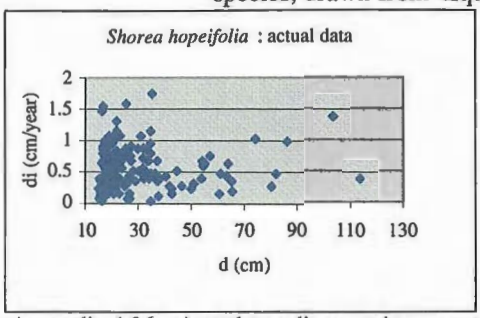


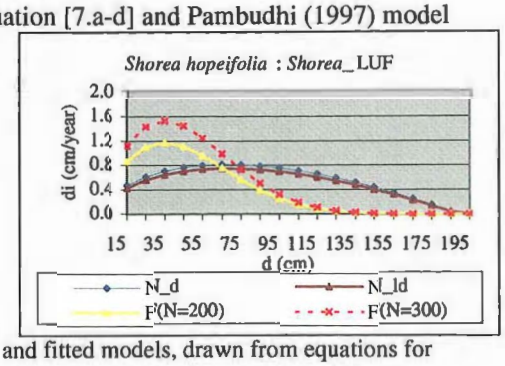
Appendix 4.25c. Group Commercial non-dipterocarp



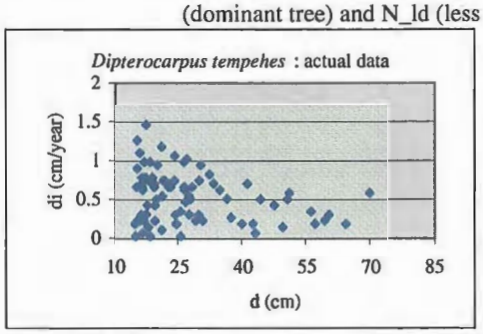
Appendix 4.25d. Group Miscellaneous

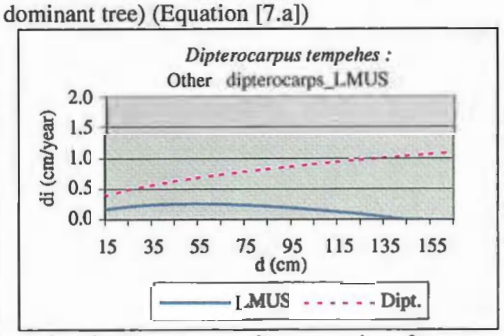
Appendix 4.26a-d. Actual tree diameter increment and fitted models for some individual species, drawn from Equation [7.a-d] and Pambudhi (1997) model



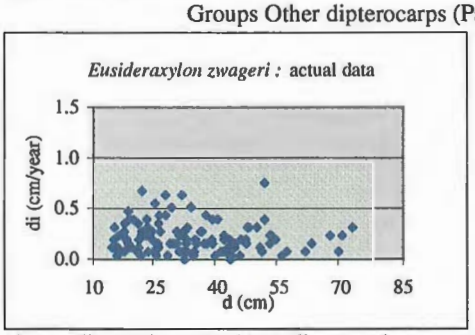


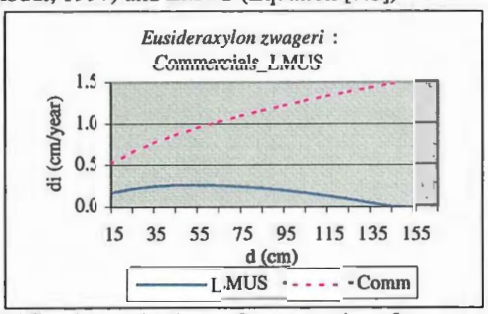
Appendix 4.26a. Actual tree diameter increment and fitted models, drawn from equations for Groups Shorea: F(N=200) and F(N=300) (Pambudi, 1997) and LUF : N_d (dominant tree) and N_ld (less dominant tree) (Equation [7.a])



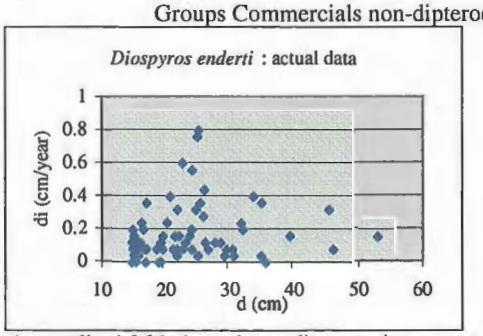


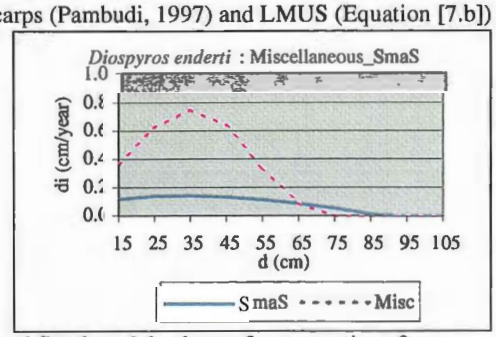
Appendix 4.26b. Actual tree diameter increment and fitted models, drawn from equations for Groups Other dipterocarps (Pambudi, 1997) and LMUS (Equation [7.b])





Appendix 4.26c. Actual tree diameter increment and fitted models, drawn from equations for Groups Commercials non-dipterocarps (Pambudi, 1997) and LMUS (Equation [7.b])





Appendix 4.26d. Actual tree diameter increment and fitted models, drawn from equations for Groups Miscellaneous (Pambudi, 1997) and SmaS (Equation [7.d])